The effect of planting density on *Pinus patula* stem form, wood properties and lumber strength and stiffness

by
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Declaration

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Summary

Faster growth and reduced harvesting age are causing a reduction in the stiffness of structural lumber from South African-grown pine plantations. A number of studies have shown the positive effects of high planting densities as a tool to improve the mean modulus of elasticity (MOE) of structural lumber. The objective of this study was to investigate the effect of planting density on stem form, wood properties and the strength and stiffness of structural lumber of young *Pinus Patula* – the most important and extensively planted commercial softwood in South Africa.

In the first part of this study, four different planting density treatments (403, 1097, 1808 and 2981 stems/ha) from an 18-year old *P. patula* spacing trial located in Mpumalanga, South Africa were sampled non-destructively. Stem slenderness, stem curvature, and the dynamic modulus of elasticity (MOE_{fak}) were measured on 171 standing trees. Increment cores were removed from 40 trees for measurement of density, microfibril angle (MFA) and ring width using the Silviscan 3 technology. Planting density had a significant effect on stem curve with the lowest planting density having the highest mean stem curve. Planting density also had a highly significant effect on stem slenderness. The MOE_{fak} increased greatly with increases in planting density. MFA was significantly influenced by both planting density and year ring number and the interaction between them. The mean MFA at similar ring numbers decreased significantly from the 403 stems/ha treatment toward the higher planting densities (1808 and 2981 stems/ha). Planting density had a limited effect on wood density. MFA seems to be the mechanism through which the tree compensates for the instability caused by a high slenderness ratio. Density, on the other hand, did not correlate with slenderness at all and was probably mostly influenced by environmental and growth factors.

In the second part of this study, a total of 37 trees from two commercial compartments, planted at different densities, were processed into 71 logs, cant-sawed into lumber, and tested for static MOE, modulus of rupture (MOR), density, and warp. The first compartment was 18 years old, planted at 1334 stems/ha and thinned to 827 stems/ha at age 11. The second compartment was 17 years old, planted at 1667 stems/ha and was unthinned. Lumber from the 1667 stems/ha compartment had a mean MOE of 8967 MPa compared to a mean MOE of 7134 MPa for the 1334/827 stems/ha compartment. Based on this evidence and results from previous studies, it seems as if planting density has a large effect on the stiffness of young *P. patula* lumber and that planting density may be used as a practical management intervention to increase the stiffness of lumber.

Opsomming

Vinnige groei en ‘n afname in rotasie-ouderdomme van SA dennehoutplantasies het ‘n afname in die styfheid van strukturele planke veroorsaak. Bestaande navorsing dui op ‘n positiewe verwantskap tussen hoë plantdigtheid en die modulus van elastisiteit (MOE) van hout. Die doelwitte van hierdie studie was om die effek van plantdigtheid te ondersoek op stam vorm, houteienskappe en die sterkte en styfheid van jong *Pinus patula* – die mees aangeplante naaldhoutspesie in SA.

In die eerste deel van hierdie studie is vier verskillende plantdigtheidbehandelinge (403, 1097, 1808 en 2981 stamme/ha), vanaf ‘n 18 jaar oue *P. patula* spasiëringsproef, geleë in Mplumalanga, SA, nie-destruktief gemeet. Stamslankheid, stamkurwe en die dinamiese modulus van elastisiteit (MOE_{fak}) is op 71 staande bome gemeet. Met behulp van die Silviscan 3 apparaat was inkrementboorsels verwyder vanaf 40 bome vir die meting van digtheid, mikrofibrilhoek (MFA) en jaarringwydte. Plantdigtheid het ‘n beduidende effek op stamkurwe getoon, met die hoogste gemiddelde stamkurwe gevind in die laagste plantdigtheidbehandeling. Plantdigtheid het ook ‘n hoogs beduidende effek op stamslankheid getoon met MOE_{fak} wat baie toegeneem het met ’n verhoogde plantdigtheid. Beide plantdigtheid en jaarring-nommer en die interaksie tussen die twee, het ‘n beduidende invloed gehad op MFA. Die gemiddelde MFA van soortgelyke jaaring-nommers het ‘n beduidende afname getoon van die 403 stamme/ha behandeling teenoor die hoër plantdigtheidbehandelings (1808 en 2981 stamme/ha). Plantdigtheid het ‘n klein invloed op houtdigtheid getoon. Dit wil blyk asof die MFA die meganisme is waardeur die boom kompenseer vir die onstabiliteit wat veroorsaak word deur ’n hoër slankheid. In teenstelling, het digtheid nie ’n korrelasie getoon met slankheid nie, maar was waarskynlik beïnvloed deur omgewings -en groeifaktore.

In die tweede deel van hierdie studie was ‘n totaal van 37 bome vanaf twee kommersiële kompartemente, geplant teen verskillende digthede, verwerk in 71 saagblokke, gekantsaag tot planke en getoets vir statiese MOE, breekmodulus (MOR), digtheid en deformasie. Die eerste kompartemente was 18 jaar oud, geplant teen 1334 stamme/ha en uitgedun na 827 stamme/ha op 11-jarige ouderdom. Die tweede kompartement was 17 jaar oud, geplant teen 1667 stamme/ha en was nie gedun nie. Planke vanaf die 1667 stamme/ha kompartement het ’n gemiddelde MOE van 8967 MPa gehad in teenstelling met ‘n gemiddelde MOE van 7134 MPa vir die 1334/827 stamme/ha kompartement. Dus, gebaseer op hierdie bewyse en uitslae van vorige studies, blyk dit dat plantdigtheid ‘n groot effek het op die styfheid van jong *P. patula* hout en dat plantdigtheid as ‘n praktiese bestuursingryping gebruik kan word om die styfheid van hout te verbeter.

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Chapter 1

Introduction

1.1. Background

The establishment of plantation forestry in South Africa in the late nineteenth century allowed the country to discontinue using indigenous forests as a source of timber (Malan, 2003). This afforestation programme enabled the country to supply its growing need for lumber. By the late 1900's, afforestation had reached over 1 million ha of land (Van Der Zel, 1997). In 2011/2012, the plantation forest cover in South Africa stood at roughly 1.3 million ha, consisting largely of pine and eucalyptus plantations (DAFF, 2014). The Mpumalanga escarpment is currently the largest saw-log growing area in South Africa making up close to half (47%) of the pine plantation area by the end of 2011 (Godsmark, 2013). The main softwood species in South Africa is *P. patula* with a total of 337 467 ha planted – accounting for roughly half of the total softwood planted area (DAFF, 2014).

Scarcity of suitable land, water legislation and conservation demands are the main factors posing a threat to the available forestry resources in South Africa (Louw, 2006). Due to these and other factors, afforestation has declined considerably in recent years (DAFF, 2014). Yields from current forestry areas are now maximized by increasing site productivity in order to meet lumber volume demands and reduce the production costs thereof (du Toit et al., 2010). Aggressive silvicultural and genetic improvement of tree resources resulted in considerably reduced rotation ages of saw-log resources (Wessels et al., 2014). The reductions in harvesting ages lead to an increased proportion of juvenile wood at final harvest. The wood produced during juvenile growth has undesirable characteristics, such as higher microfibril angle and lower wood density, which in turn results in lower lumber stiffness and strength (Malan, 2010).

Various studies in South Africa have reported reduced mechanical properties of SA pine (Wessels et al., 2011; Dowse and Wessels, 2013; Wessels et al., 2014), specifically the modulus of elasticity (MOE) – a property of great importance in South Africa in terms of structural lumber performance (Wessels and Petersen, 2015).

Several investigations showed that planting at higher stand densities improves the stiffness of young coniferous trees with some showing increased planting density to be even more effective than genetic improvement (Lassere et al., 2004; Lasserre et al., 2005; Roth et al., 2007; Waghorn et al., 2007; Lassere et al., 2008). Lassere et al. (2005) reported gains attributable to genetics to be only 47% that of gains through planting at high stand densities. Moore et al. (2015) reported that, apart from density, wood properties were more sensitive to tree spacing than differences in genetic material of *P. radiata*. For mechanical tests done on lumber, Foneman (2014) showed planting densities to positively influence the MOE of young South African grown *P. elliottii*.

1.2. Objective

The objective of this study was to evaluate the effect of planting density on stem form, wood properties and lumber strength and stiffness. Although there was an interest in a number of properties the emphasis in the study was on the stiffness of lumber and the characteristics influencing it.

1.3. Structure of thesis

At the time of this study there was not a suitable *Pinus patula* spacing trial available for destructive testing. Two separate investigations were, therefore, completed: In the first investigation an 18-year old *Pinus patula* spacing trial close to Barberton, Mpumalanga was non-destructively sampled to determine the effect of spacing on stem form, microfibril angle (MFA), and wood density. In the second investigation two commercial *Pinus patula* compartments, which were planted at different densities, were destructively sampled to determine the effect of planting density on the flexural properties of full-sized lumber.

The investigations were reported in the format of two independent scientific journal articles – chapters 2 and 3 of this thesis. The author of this thesis is the main author for each of the two articles with input to parts of the manuscripts from the co-author, C.B. Wessels, who conceptualised and supervised each study. A final chapter (chapter 4), summarises the results and conclusions of this thesis.

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Chapter 2

The effect of planting density on *Pinus patula* stem form, microfibril angle and wood density

Abstract

Faster growth and reduced harvesting age are causing a reduction in the stiffness of structural lumber from South African grown pine plantations. Microfibril angle (MFA) and density are known to be two of the basic wood properties influencing stiffness. The objective of this study was to determine the effect of planting density of *Pinus patula* trees on the MFA, wood density as well as the stem form of trees. Four different planting density treatments (403, 1097, 1808 and 2981 stems/ha) from an 18-year old *Pinus patula* spacing trial located in Mpumalanga, South Africa were sampled non-destructively. Stem slenderness, stem curvature, and the dynamic MOE were measured on 171 standing trees. Increment cores were removed from 40 trees for measurement of density, MFA and ring width using the Silviscan 3 technology. Planting density had a significant effect on stem curve with the lowest planting density having the highest mean stem curve. Planting density also had a highly significant effect on stem slenderness. The dynamic MOE on standing trees (MOE_{fak}) increased greatly with increases in planting density. MFA was significantly influenced by both planting density and year ring number and the interaction between them. The mean MFA at similar ring numbers decreased significantly from the 403 stems/ha treatment toward the higher planting densities (1808 and 2981 stems/ha). Planting density had a limited effect on wood density. MFA seems to be the mechanism through which the tree compensates for the instability caused by a high slenderness ratio. Density, on the other hand, did not correlate with slenderness at all and was probably mostly influenced by environmental and growth factors.

Keywords: *planting density; Pinus patula; modulus of elasticity; structural timber; MFA; wood density*

1. Introduction

There are two critical issues for the financial sustainability of structural lumber producers in South Africa. In the first place their products must conform to the minimum product mechanical requirements to be able to grade and sell it as structural grade lumber. Secondly, the cost of production, which is greatly influenced by volume recovery, must be competitive to alternative structural products, such as steel and imported structural lumber. Previous research studies suggest that the planting density of softwoods might influence both these issues. Higher planting density showed increased mechanical properties of wood in some studies (i.e. Froneman, 2014; Lasserre et al., 2009; Roth et al., 2007) and less stem deformations, which influences the volume recovery (Froneman, 2014).

About 75% of lumber produced and sold in South Africa is regarded as structural lumber (Crickmay and Associates, 2015), making it the single most important product category for local sawmills. Stiffness, referred to as the modulus of elasticity (MOE), is a measure of a material's resistance to deform when subjected to a bending stress or a compressive load in the case of slender members. It is considered one of the most important mechanical properties of structural grade lumber (Wessels et al., 2015b; Wessels and Petersen, 2015) and accordingly has strict minimum requirements set out in the SANS 10163-1(2009) standard.

Due to rapid growth, the harvesting age of South African-grown saw log pine has reduced considerably from about 28 years in 1983 to about 23 years in 2003 (Wessels et al., 2015a). Since then, South African studies have shown a significant reduction in important mechanical properties, particularly the mean MOE of structural grade lumber (Burdzik, 2004; Wessels et al., 2011; Dowse and Wessels , 2013) – presumably due to an increase in the juvenile wood proportion. Dowse and Wessels (2013) and Wessels et al. (2014) reported the mean MOE of 16-20 year-old *P. patula* lumber to be about 25% less than required for the lowest and most produced structural grade in South Africa. *Pinus patula* is the main planted species in South Africa accounting for up to 52.2% of the total softwood area as of 2012 (DAFF, 2014). It is therefore essential that lumber produced from this species conforms to specifications. In light of these reports, the South African sawmilling industry needs to address the low MOE of *P. patula* and other softwood resources to continue the processing thereof into acceptable structural products.

Possible approaches may include improving the resource through tree breeding or increasing planting densities (Wessels et al., 2014). Research on *P. radiata* has shown the positive effects of planting at high stand densities on the stiffness of wood (Lasserre et al., 2005; Waghorn et al, 2007a; Roth et al., 2007; Lasserre et al., 2009). The increase in MOE due to increasing stand densities has been largely attributable to the increase in the height/diameter ratio (slenderness) as tall slender trees require higher stiffness wood to prevent buckling and bending failure due to its increasing self-weight and wind loading. This understanding is in agreement with Euler's buckling theory and the bending stress theory (Watt, et al., 2006; Merlo et al., 2014; Wessels et al., 2015b).

Mechanical properties, such as MOE, are determined by the structural composition of the cell walls of tracheids (Barnette and Bonham, 2004; Moore et al., 2014). For softwoods, the MFA is the orientation of cellulose microfibrils in the secondary cell wall with respect to the longitudinal axis of tracheid cells. MFA and wood density have been shown to be the two most influential properties for *P. radiata* (Cown et al., 1999; Downes, et al., 2002; Xu and Walker, 2004) and *P. patula* (Wessels et al., 2015a) MOE. However, a poor relationship between MOE and density of *P. radiata* corewood has been reported in some studies (Britton and Burdon, 2001; Lasserre et al., 2009; Watt et al., 2010). Research by Cown et al. (1999) noted that density in *P. radiata* does become more influential in outerwood.

The strong influence of MFA on the MOE of wood has been well documented (Cave and Walker, 1994; Walker and Butterfield, 1996; Evans and Ilic, 2001; Moore et al., 2014; Wessels et al., 2015a). According to Cave and Walker (1994), MFA is considered the only property to account for large variations in radial MOE trends in fast grown softwoods with density acting only as a supporting property. This view is supported by Walker and Butterfield (1996) who argue that the increase in stiffness from pith to bark is attributable to an increase in the quality (referring to MFA) of cell material rather than only the increase in quantity (referring to density) thereof. Interestingly, research relating the average MFA to the stiffness of full-sized lumber instead of small clear specimens has shown density to have a similar effect on board MOE (Wessels et al., 2015a), and in some cases an even larger effect than MFA (Downes et al., 2002; Cown et al., 2004; Vikram et al., 2011).

Studies on the variation of MFA for *P. radiata* has been well documented (Cown et al., 1999; Burdon et al., 2004; Xu and Walker, 2004; Watt et al., 2010; Moore et al., 2014). The variation of MFA in *P. radiata* is expected to gradually decrease from the pith till about the 10th year ring. Although the average MFA decreases from the base of the stem upwards, the pith to bark trend remains fairly constant. Compared to *P. radiata* grown in New Zealand, Wessels et al. (2015a) observed a similar trend of MFA from pith to bark of *P. patula* at a height of 1.3m above ground but found the MFA to be approximately 10° smaller at similar rings from the pith.

The form of tree stems has a large influence on value recovery of lumber products. Both the yield and quantity of lumber is greatly affected by crooked stems (Lachenbruch et al., 2010) and some studies suggest value losses of roughly 10% due to stem curvature (Carino et al., 2006). Stem sweep and curvature affect the overall volume of harvestable saw-logs.

Additionally, leaning stems and those with excessive sweep are known to cause compression wood (Timell, 1986). According to Theron and Bredenkamp (2004) trees grown under suppressed conditions from high stand densities are likely to display poor stem forms. Froneman (2014) however reported spacing treatment to have a significant effect on tree shape defects, but with no obvious trend for different species across a range of planting densities. Some species such as *P. radiata* and the *P. elliottii x caribaea* hybrid showed more stem defects for less dense stands, but trends were not consistent.

The objective of this study was to determine the effect that planting density of *Pinus patula* trees have on the important properties of stem form, MFA and wood density. The results of the study would be useful in formulating future forest management regimes for *Pinus patula* grown in South Africa.

2. Materials and methods

2.1 Experimental layout

This study was conducted using an 18 year-old experimental spacing trial consisting of *Pinus patula* trees located in the Mpumalanga escarpment at the Montrose plantation near Barberton (see Appendix A, B and C). This area receives about 672 mm of rain per year with average midday temperatures ranging from 20.2°C in June to 26.8°C in January. The trial received pruning at ages five, seven and nine years to a height of 2 m, 3.5 m and 5.5 m respectively. Two replications of four planting density treatments viz. 403, 1097, 1808 and 2981 stems/ha were used. Each sampling plot had been planted with 49 seedlings in a 7x7 layout but only the centre 25 trees (excluding the buffer trees) were included in the study. Out of a possible 200 trees only 171 were still available due to mortality (Table 1). All the available trees were used to non-destructively measure DBH, height and the dynamic MOE. Increment cores were removed from ten trees per planting density treatment to measure MFA and density.

Table 1: Sampled plot details and site means.

Planting density (stems/ha)	Mean DBH (cm)	Mean height (m)	n (DBH, height, MOE_{fak})	n (MFA, density)
403	32.7	23.3	48	10
1097	23.8	21.5	48	10
1808	19.9	20.6	42	10
2981	16.9	20.3	33	10

2.2 Measurements

A terrestrial laser scanning system was used to scan one replication of each planting density treatment. The 3D Forest version 0.31 software package was used to provide detailed information on forest parameters processed from a cloud of points acquired by terrestrial laser scanning (Figure 1). The information was used to obtain the form of individual trees in a particular plot specifically identifying the stem curve. The application could extract tree parameters such as the DBH, the position of each stem and the stem curve up to a limited height of the tree. Tree heights were, however, unobtainable as there was too much noise present in the canopy region which could not be distinguished from the actual tree stem (see Figure 1).

Of particular interest in this study though was the curvature of the stem up to the first 6 m height. This portion of the stem usually represents more than half of the stem value and, importantly, measurements on this pruned bottom section could be obtained accurately without interference of branches.

In this study, the curve of a tree stem was defined as the maximum deviation from the stem's centreline perpendicular to the imaginary straight line (chord) joining the two centre-points of the stem from 0 to 6 m (Figure 2). These measurements were recorded for a range of vertical heights above ground (Figure 3). The perpendicular distances were then derived through vector equations using 3-dimensional coordinates of tree parameters extracted from the software 3D Forest. The stem curve was then calculated from the set of perpendicular distances for each tree by selecting the maximum of these distances.

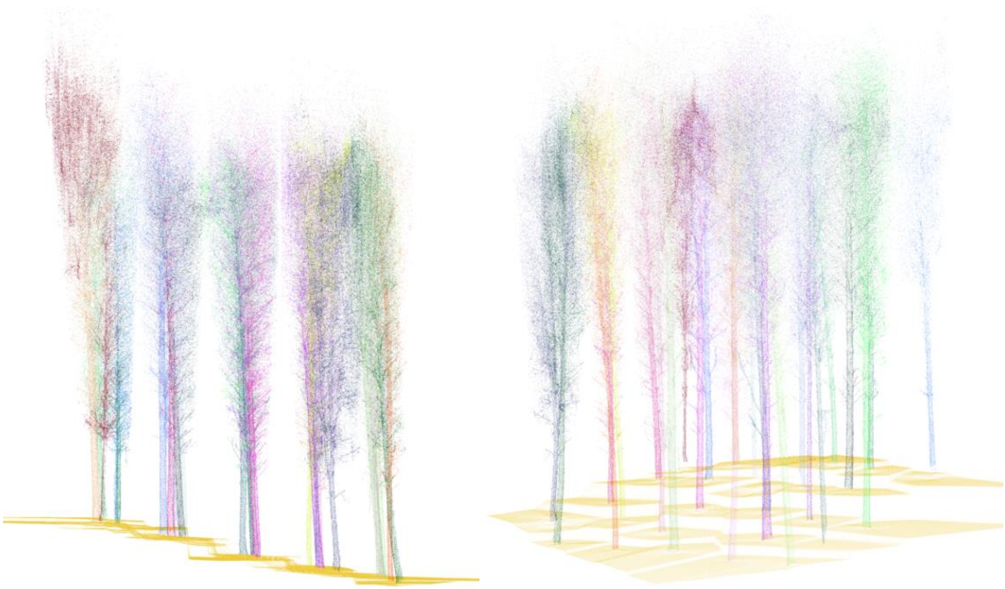

Figure 1: Point clouds of individual trees captured by terrestrial laser scanning

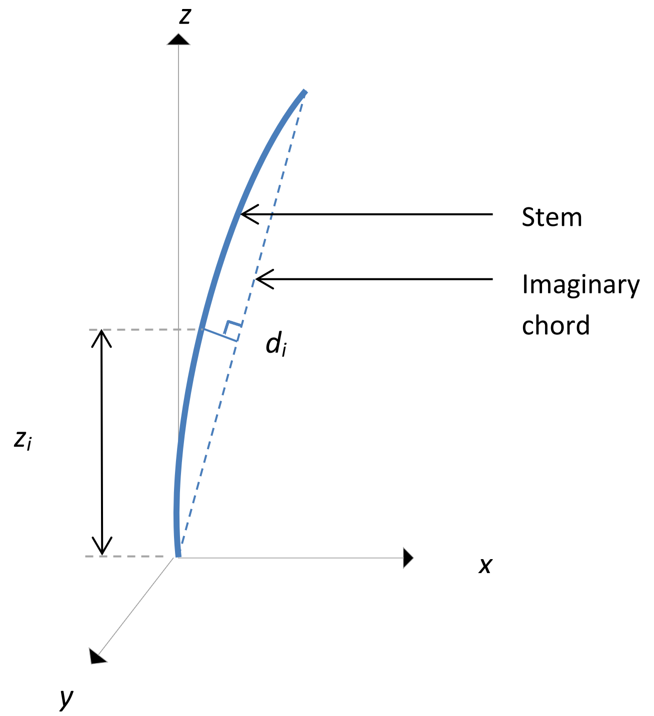

Figure 2: Illustration of the measurement of stem curve using the center coordinates of stem diameters taken at vertical distances from the ground (z_i) for i = 0.65, 1.3, 2, 3, 4 and 5 meters to obtain the perpendicular distances (d_i) between the stem curvature and chord joining its ends in a 3-dimensional space.

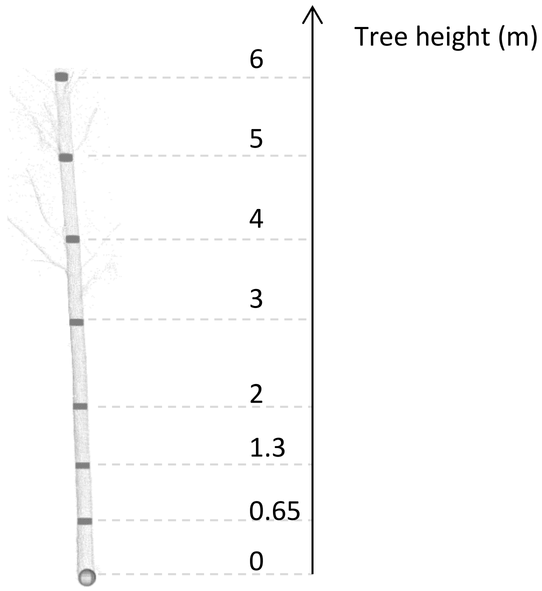

Figure 3 : Stem curve extracted from 3D Forest

In field, the DBH and standing tree height were manually recorded for all trees examined. The dynamic MOE of the outerwood of standing trees was calculated from stress wave velocities at breast height. The transit time of stress waves was recorded using the Fakopp Treesonic instrument. A transmitting probe and receiving probe were inserted approximately 1 m apart centred at breast height into the tree stem where a stress wave was induced through the impact of a hammer on the back end of the transmitting probe. With a known distance between the two probes the velocity of the wave was calculated using the time of flight (TOF) which was automatically recorded and displayed on the instrument. Three measurements were recorded on both the north and south-facing surfaces of the tree stem. From the wood density (ρ), the velocity of the stress wave (V), and the dynamic modulus of elasticity (MOE_{fak}) of each tree was calculated using the following formula:

$$\mathrm{MOE_{fak}} = \rho V^2 \quad (1)$$

In practice, the green density of trees has often been assumed constant at 1 000 kg/m^3 for *P. radiata (Lassere et al., 2004; Wessels et al., 2011; Froneman, 2014)*. According to Malan (2010), the average green density of standing SA pine trees is relatively constant, varying between 1000 and 1200 kg/m^3. Wielinga et al. (2009) found the variation of *P. radiata* green density to have little impact on the variation of the dynamic MOE making acoustic velocity the most important value in its determination. This is supported by Nilsson (2014), who found little variation between using a constant (1000 kg/m^3) and observed green density of selected pine species in South Africa, including young *P. patula* – making it an adequate approach. The probes of the Fakopp Treesonic instrument penetrate into about 10-15 mm of the stem surface (excluding the bark).

Five increment cores were extracted from each plot, resulting in a total of 40 increment core samples - 10 from each planting density treatment. The trees selected to collect these increment cores were randomly chosen from trees which had most, if not all of their neighbours still alive to give a good representation of the competition experienced in a given stems/ha plot. The cores were removed at breast height (1.3 m) from the northern side for each of the 40 trees selected. Water was replaced by ethanol in three stages before the cores were dried to equilibrium moisture content.

The MFA and wood density of each sample were measured using the Silviscan 3 technology at a resolution of 2 mm and 0.025 mm for MFA and density respectively. The average MFA and density were recorded on an annual ring basis according to annual rings defined by the radial density profile. Any analysis involving the mean MFA, density and ring width excluded the first and last year rings of individual increment cores. The reason for this exclusion was because even though cores were extracted at a constant height of 1.3 m, the growth of individual trees varied so the first year rings were not complete full annual rings. In other words it contained mostly late wood for the first annual rings and mostly early wood for the last annual rings as tree were harvested just before winter.

2.3 Data analysis

The software programs R Core Team (2014) and Statistica (Dell Inc, 2015) were used for statistical analysis. One-way analysis of variance (ANOVA) was done for tree variables and the dynamic MOE with planting density treatment as the categorical variable. A mixed model repeated-measures ANOVA was also performed to test for any statistical significance for the effect of spacing treatment and rings from pith as the main effects, and their interactions with MFA, density and ring width as independent variables.

3. Results and discussion

The results for stem form will firstly be reported followed by effect of planting density on tree variables - tree height, DBH and MOE_{fak}. Finally, results for MFA, density and ring width will be reported and discussed.

3.1 Stem form

The DBH values obtained through terrestrial laser scanning correlated strongly with the physically measured DBH (R^2 = 0.991) – indicating the precision of the laser scanning system.

A total of 81 trees were evaluated for stem form. The results are shown in Table 2. Note that these values are the minimum, maximum and mean of the maximum stem deviations as previously explained. Spacing treatment had a significant effect (p = 0.00010) on the average stem deviation up to 6 m (Figure 4). However, no obvious trend across spacing treatments was observed. The least densely planted spacing treatment (403 stems/ha) had the most stem curve with a mean of 83.1 mm. The 403 stem/ha plot also had the tree with the highest stem curve of any tree evaluated – 220.2 mm. Stem curve for trees from the 1097 stems/ha treatment was significantly lower than for trees from the 403 stems/ha treatment. On average, this plot displayed the lowest stem curve (40.7 mm). Similarly, it also had the lowest maximum stem curve between all spacing treatments (Table 2). There were no significant differences in stem curve between 1808 stems/ha and 2981 stems/ha. The means for these plots were both higher and lower than the 1097 stems/ha and 403 stems/ha treatments respectively.

Table 2: Minimum, maximum, mean and standard deviation (sd) values of the maximum deviation of stems for each spacing treatment

Spacing treatment (stems/ha)	Valid n	Stem curve			
		Min	Max	Mean	sd
403	22	18.7	220.2	83.1	44.9
1097	24	16.7	102.0	40.7	18.3
1808	19	40.3	132.0	70.4	22.2
2981	16	15.0	109.7	55.5	30.6

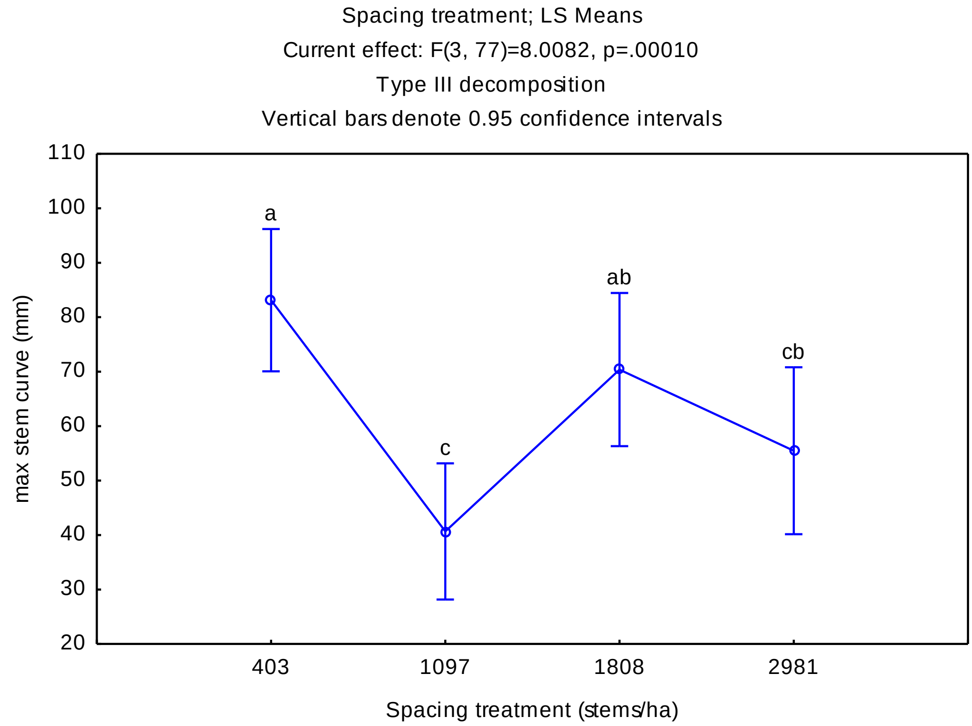

Figure 4: Means and 95% confidence intervals for stem curve for each spacing treatment. Different letters denote significant differences

There might be a number of factors which influenced tree form in this study. According to some studies, trees growing in suppressed conditions often display poor stem form (Theron and Bredenkamp, 2004). This might lead to stem deformations in very densely planted stands where growth will be severely suppressed. On the other hand, competition for sunlight from evenly planted neighboring trees can help direct growth straight upwards and also improve stem form. One only has to look at the poor stem form of free-growing trees next to a plantation as support for this argument (although a lack of pruning and poor branching structure could possibly also influence the stem form of free growing trees). It might be possible in this study that the two denser planting treatments experienced so much competition for growth resources that severe growth suppression resulted and therefore the mean stem curve was higher than the 1097 stems/ha treatment. The 403 stem/ha treatment, however, might have been too close to free growing trees and, therefore, for this very different reason developed poor stem form. More work is required on *Pinus patula's* stem form, its root causes, and possible improvement.

Another factor that should be considered in future work, but did not play a role in this study, is the influence of thinning. It might be true that the higher planting densities did not always result in the best stem form, but when thinning is performed, higher planting densities give the opportunity to remove more trees with poor stem form. With a planting density of 1097 stems/ha and a final target stand density of 650 stems/ha only 547 stems/ha can be removed during the thinning operation. With a planting density of 1808 stems/ha and a target density of 650 stems/ha a total of 1158 stems/ha will be removed during thinning. It is therefore probable that the remaining trees of the 1808 stems/ha planting density will have much better stem form than the remaining trees of the 1097 stems/ha treatment.

3.2 DBH and height

The results for DBH and height for all spacing treatments are shown in Table 1. A one-way ANOVA was done for each effect to test for any statistical differences between the means. Spacing treatment had a significant effect ($p<0.001$) on DBH as shown in Figure 5. As expected, a clear decreasing trend in the mean DBH in denser stands is displayed. The mean DBH was highest (32.7 cm) for the 403 stems/ha spacing treatment and lowest for the 2981 stems/ha spacing treatment (16.9 cm). Tree height was also significantly influenced by spacing treatment ($p<0.001$) (Figure 6). Tukey's LSD post hoc test revealed that only the mean height for 403 stems/ha differed significantly from the rest (see Figure 6) although a trend was clear with tree height deceasing with denser spacing treatments. On average, the largest tree heights were found for the 403 stems/ha spacing treatment. Tree height decreased by about 8% from 403 stems/ha to 1097 stems/ha. A further decrease in tree height of only about 5% between 1097 stems/ha and 2981 stems/ha is displayed (Table 1). In comparison, DBH was much more severely influenced by planting density with a decrease in DBH of 48% from the lowest planting density (403 stems /ha) to the highest planting density (2981 stems/ha).

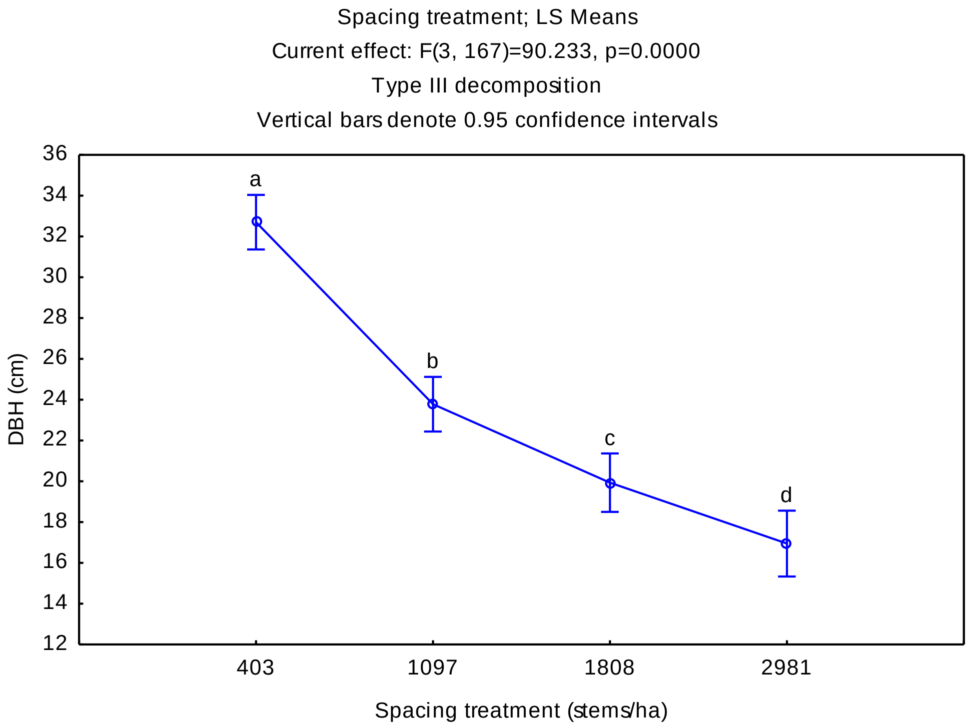

Figure 5: Means and 95% confidence intervals of tree height for each spacing treatment. Different letters denote significant differences

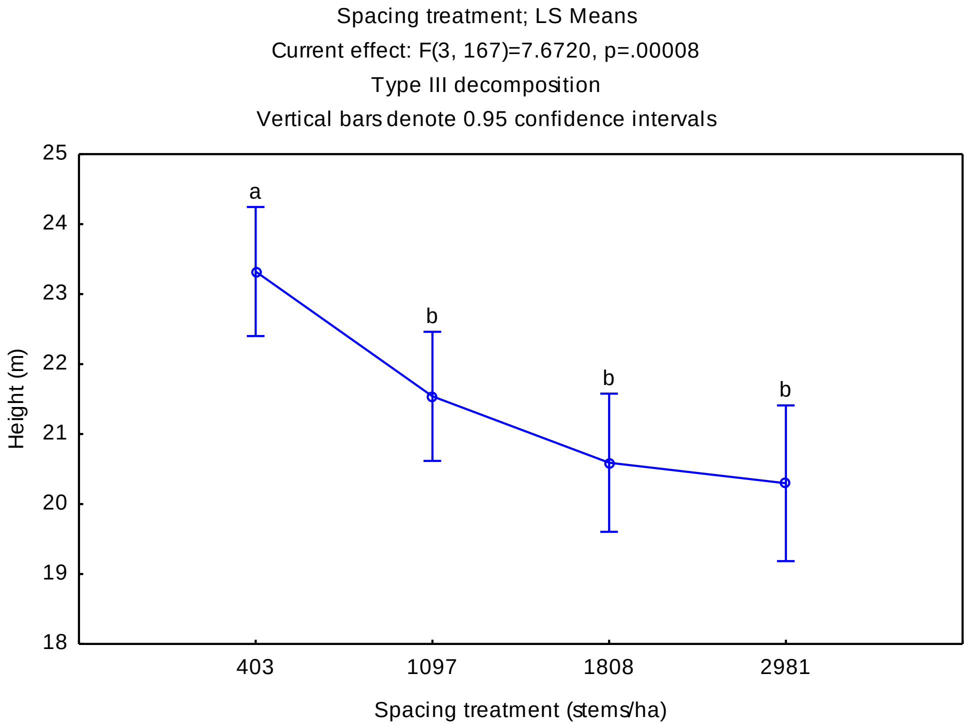

Figure 6: Means and 95% confidence intervals of tree height for each spacing treatment. Different letters denote significant differences

3.3 Slenderness

The mean slenderness values – taken as the ratio of tree height to the diameter at breast height – for each spacing treatment can be seen in Table 3. The effect of planting density on slenderness was significant ($p<0.001$). As expected, the ratio increased with increasing planting density with significant differences indicated in Figure 7. A rather high increase of 68% from the 403 stems/ha treatment to the 2981 stems/ha spacing treatment was displayed in relation to the 49-52% found by other studies across roughly the same range of planting densities on young *P. elliottii* (Foneman, 2014), and *P. radiata* (Waghorn et al., 2007a). Slenderness was more influenced by DBH than height, which stayed relatively similar (see previous section)

Table 3: Mean MOE_{fak} and stem slenderness for each planting density treatment

Planting density (stems/ha)	Slenderness	MOE_{fak} (MPa)	
		Mean	sd
403	0.73	10150	2192
1097	0.92	12739	2206
1808	1.06	14607	3973
2981	1.23	15044	2616

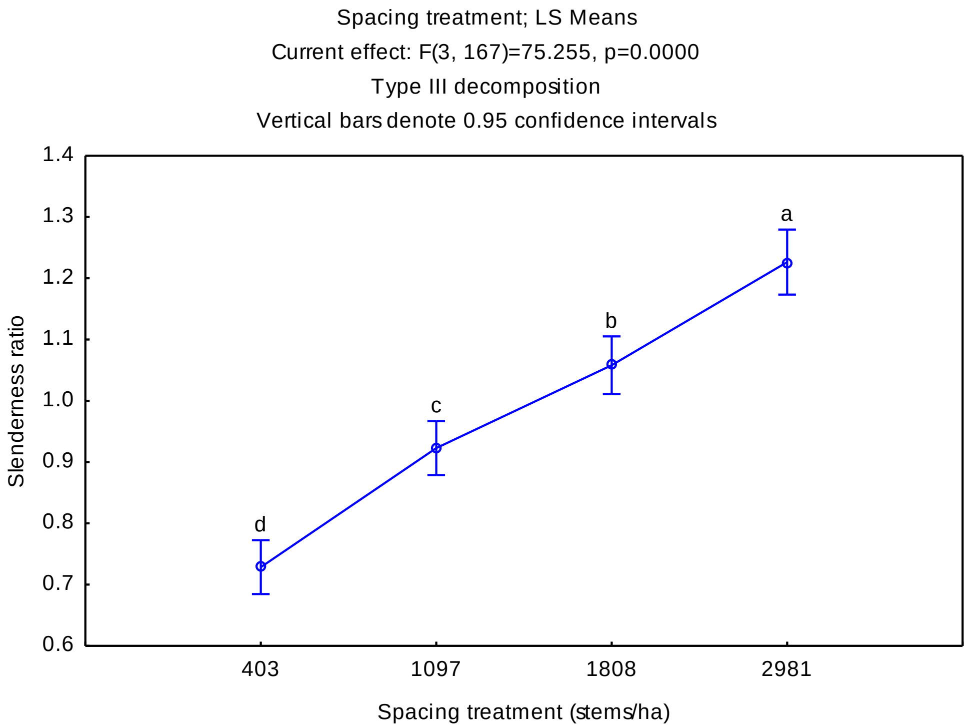

Figure 7: Means and 95% confidence intervals for stem slenderness for each spacing treatment. Different letters denote significant differences

3.4 Dynamic modulus of elasticity (MOE_{fak})

The results for MOE_{fak} for each spacing treatment are shown in Table 3. Stress wave measurements were averaged for all recordings on both the north and south side of the stem. Spacing treatment had a significant effect on MOE_{fak} ($p<0.001$). The *P. patula* trees followed an increasing trend of higher MOE_{fak} calculated for denser stands (Figure 8). The mean MOE_{fak} was lowest for the 403 stems/ha treatment at 10150 MPa, followed by the 1097 and 1808 stems/ha treatments with 12379 MPa and 14607 MPa respectively and the highest for 2981 stems/ha at 15044 MPa. The MOE_{fak} increased by 48% along the four spacing treatments from 403 stems/ha to 2981 stems/ha. Differences in means were the greatest between the 403 stems/ha and 1097 stems/ha planting density treatments (increasing by 26%) and thereafter displaying smaller differences between denser spacing treatments.

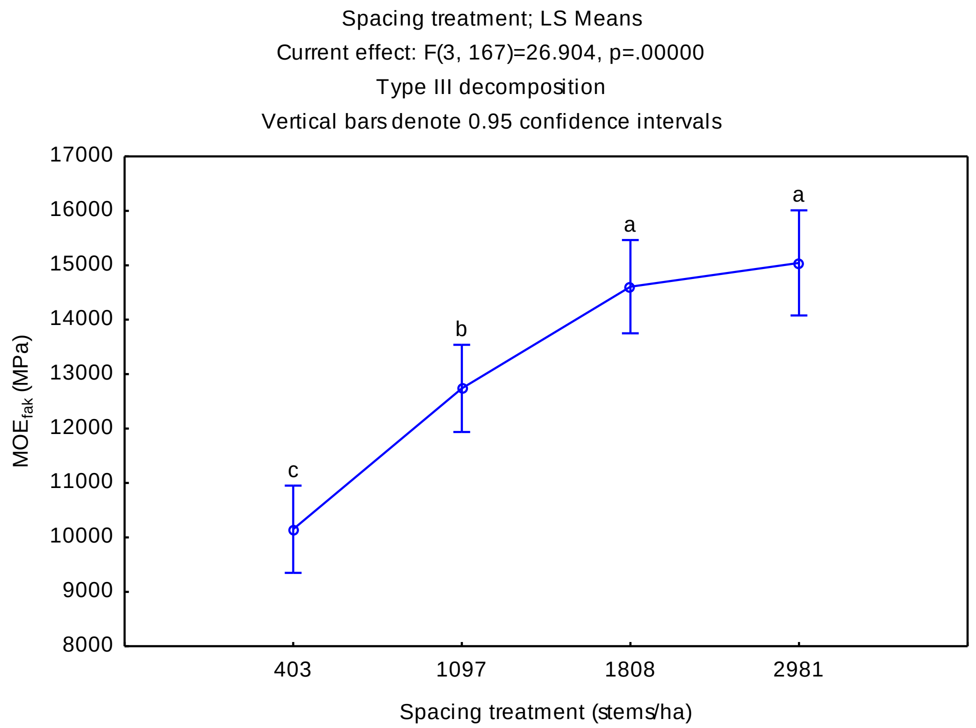

Figure 8: Means and 95% confidence intervals of MOE_{fak} for each spacing treatment. Different letters denote significant differences

The strong positive influence of planting density on MOE_{fak} was higher than that found in other studies. Waghorn et al. (2007b) reported an increase (39%) in the mean dynamic MOE, calculated from stress wave velocities of standing trees, across 10 different planting densities ranging from 209 stems/ha to 2551 stems/ha. The mean MOE_{fak} values for 12 year-old South African-grown *P. elliottii* was 33% higher for 2981 stems/ha spacing compared to 403 stems/ha spacing (Froneman, 2014). In that study, mean MOE_{fak} values of 20 year-old *P. radiata* for 2981 stems/ha also exceeded those for the 403 stems/ha spacing by about 33%. It thus seems as if *Pinus patula* is a species where planting density has a relatively large impact on the dynamic MOE of the outerwood of tree stems compared to other investigated softwood species. .

The relationship between individual tree slenderness and MOE_{fak} was quite poor (R^2 = 0.19) in this study. Various other studies found a good linear relationship between the slenderness ratio and MOE. Results by Watt et al. (2006), Waghorn et al. (2007b), Watt et al. (2009) and Lassere et al. (2009) found slenderness to explain 49-71% of the variation in tree MOE. Interestingly, Lassere et al. (2008) found stem slenderness to seemingly account for variation in tree MOE as a previously significant effect of initial spacing became non-significant once adjustments were made for differences in slenderness (adding slenderness as a covariate) – suggesting tree slenderness to be the sole mechanism through which high planting densities improve wood stiffness. Contrastingly, Roth et al. (2007) found the effect of planting density on MOE to be only less significant after adjustments for stem slenderness with the author suggesting environmental and genetic factors to control the (outerwood) dynamic MOE of young *P. taeda* through mechanisms other than stem form.

The rationale behind slender trees equalling higher stiffness is that tall cylindrical-like stems require higher stiffness to prevent stem buckling as opposed to more conical stems. However trees with sufficient wood stiffness might not require the production of stiffer wood material and therefore, in this case, tree stiffness might not display a strong relationship with the slenderness of trees (Wessels and Froneman, 2015). The poor relationship between stem slenderness and MOE_{fak} in this study suggests that other factors might also play a role in *P. patula* outerwood tree dynamic MOE than only slenderness.

Table 4: Mean microfibril angle, density and ring width at different rings from pith and for each spacing treatment. Different letters denote significant differences

Wood Property	stems/ha	Rings from pith											
		2	3	4	5	6	7	8	9	10	11	12	13
Microfibril angle (°)	403	31	30	27	24	20	18	15	14	12	12	12	12
		a	*ab*	*cb*	*d*	*fe*	*fg*	*ihk*	*ijkl*	*pjo*	*plmo*	*ijklno*	*plmoq*
	1097	31	29	23	16	12	10	9	9	8	7	8	8
		a	*ac*	*de*	*igj*	*pkq*	*plmoqr*	*psn*	*so*	*sr*	*s*	*sr*	*sr*
	1808	25	23	18	13	9	8	7	7	7	7	8	9
		cd	*de*	*fgh*	*ijklno*	*pso*	*sr*	*sr*	*sr*	*sr*	*sr*	*sq*	*pso*
	2981	28	26	19	13	10	10	9	9	9	10	10	10
		ac	*cd*	*feg*	*ijkm*	*psl*	*psn*	*ps*	*psn*	*psn*	*psl*	*psl*	*psl*
Density (Kg/m^3)	403	406	429	422	442	454	446	460	459	502	469	464	479
		xzv	*xry*	*xzs*	*opqrstuvw*	*ompqrstu*	*opqrstuvw*	*olnqrstu*	*olqrstu*	*gdehijkn*	*oiqr*	*ojkqrt*	*ohq*
	1097	396	405	421	467	468	466	496	517	565	551	544	505
		xzw	*xzu*	*xzq*	*ojrst*	*ojrst*	*ojrst*	*god*	*gdehik*	*abc*	*abce*	*abcef*	*gdfhijklm*
	1808	367	372	406	433	474	479	513	513	599	541	511	496
		z	*zy*	*xzu*	*xqs*	*ohqrs*	*ohr*	*gchijkl*	*gchijkl*	*a*	*gb*	*gchijklm*	*gode*
	2981	385	373	412	453	473	496	531	552	591	558	531	524
		xz	*zy*	*xzt*	*omnqrstuv*	*okqrs*	*gehijklp*	*gch*	*abcd*	*ab*	*abcd*	*gchi*	*gchij*

Table 4: Continued

Wood property	stems/ha	Rings from pith											
		2	3	4	5	6	7	8	9	10	11	12	13
Ring width (mm)	403	23	19	17	11	9	9	6	5	4	4	3	3
		a	*bc*	*de*	*h*	*i*	*i*	*kjl*	*kjlm*	*klmnopq*	*klmnopqr*	*sn*	*sm*
	1097	21	17	13	7	5	4	3	3	3	2	2	2
		b	*de*	*hg*	*ij*	*kjlmn*	*klmnop*	*sm*	*so*	*so*	*sq*	*sq*	*s*
	1808	17	18	13	7	5	4	3	3	2	2	2	2
		dce	*dc*	*fg*	*ij*	*klmno*	*sl*	*so*	*so*	*s*	*sp*	*sp*	*so*
	2981	16	15	11	6	4	3	3	2	2	2	2	2
		de	*fe*	*hg*	*kj*	*sm*	*sn*	*so*	*sp*	*s*	*s*	*sr*	*sp*

3.5 Microfibril angle

In the mixed-model repeated measures ANOVA, trees were used as a random effect while the other factors were fixed. The increment cores were removed at breast height (1.3 m) and trees may take about one to four years to reach this height. The ring numbers are thus not equal to the age of the tree. In addition, the first and last annual ring were excluded from the study and therefor only the 2nd to 13th annual rings were considered, as some factor combinations were too few beyond the 13th annual ring. Results for MFA showed a highly significant interaction between rings from pith and spacing treatment (Table 5). The variation of MFA from pith to bark and for each spacing treatment level is illustrated in Figure 9.

Table 5: ANOVA table for microfibril angle with ring from pith and spacing treatment as factors (shaded effects were significant at $p<0.05$)

Source of variation	Num. df	Den. df	F	P
Spacing	3	36	10.8102	<0.0001
Rings from pith	11	370	206.0684	<0.0001
Rings from pith*Spacing	33	370	2.6044	<0.0001

The mean MFA per annual ring in *P. patula* across all spacing treatments varied between 7°and 31° from the 13th to the 2nd year ring (Table 4 and Figure 9). MFA was significantly different depending on the ring number from pith and the spacing treatment. The mean annual MFA for the 403 stems/ha planting density treatment varied from just over 10° at the 13th annual ring to just over 30° at the 2nd annual ring.

For tree rings 2-9 post hoc comparisons using Fisher's LSD test revealed significant differences in MFA between most of the equivalent annual rings of the 403 stems/ha treatment and the other treatments (Table 4). The MFA values of treatments 1808 stems/ha and 2981 stems/ha were not significantly different at similar year rings (Table 4) – MFA could therefore be considered similar for those two treatments. The only significant difference in MFA for equivalent annual rings between trees from the 1097 stems/ha treatment and those from 1808 stems/ha was near the pith (the 2nd to 4th annual ring), where the MFA of trees for the 1808 stems/ha treatment was on average 5.4° lower than for 1097 stems/ha. This is an important difference since it forms part of the pith board, which usually has the worst MOE in the log. In trees harvested at a young age, pith boards constitute a large percentage of the total recovered product. Rings closer to the bark, with better mechanical properties, are unfortunately is less prevalent as they are mostly chipped away in the sawmilling process.

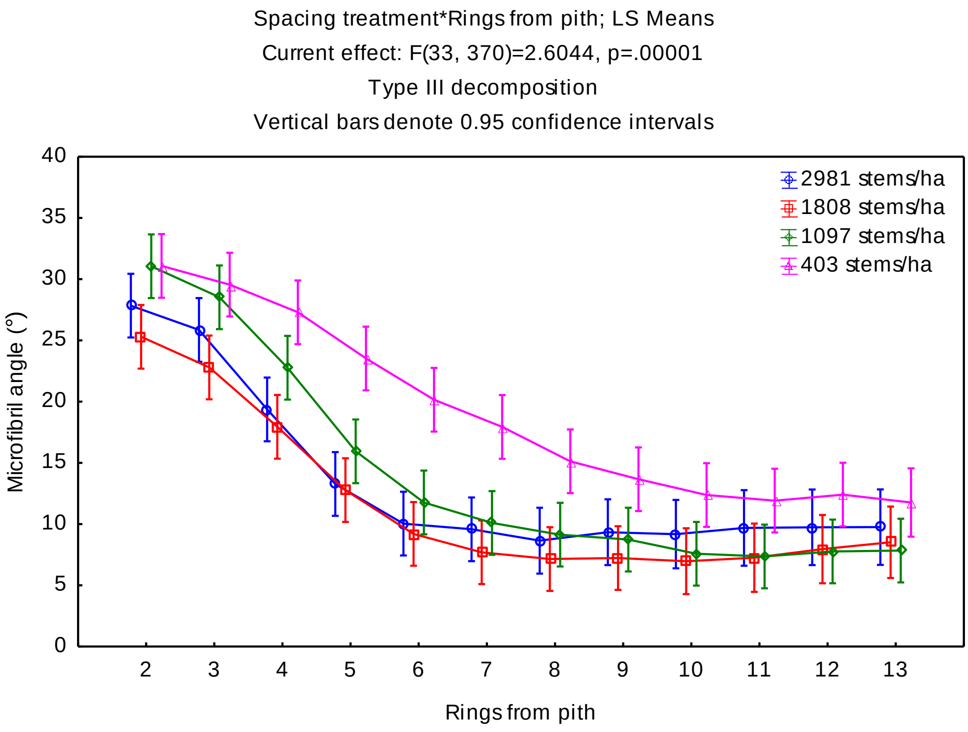

Figure 9: Variation in microfibril angle at different spacing treatments and rings from pith. Vertical bars denote 95% confidence intervals.

Differences in the mean annual MFA between spacing treatments were most pronounced between 403 stems/ha and other treatments. The mean MFA for the 403 stems/ha treatment rapidly decreases to about the 11th annual ring before it then stabilises at about 12°. All the denser spacing treatments decrease up to the seventh and eighth annual ring before stabilising (Figure 9). This difference highlights how the competition experienced by the densely planted treatments favourably reduces the mean MFA for equivalent annual rings especially between the 5th and 10th annual rings. The transition from juvenile to mature wood is often defined as the radial position where wood properties have stabilised in terms of the rate of change – usually after a transition zone (Zobel and van Buijtenen, 1989; Cown, 1992). When only considering MFA it seems as if this transition then occurs earlier for denser planting spacing treatments compared to wider spacing treatments.

Across all spacing treatments the mean MFA at the second annual ring ranges from 25° to 31°. The high MFA near the pith is expected as saplings with small diameters require more flexibility of the stem to prevent fracture of the stem when subjected to wind loading (Barnette and Bonham, 2004).

The variation and trend in the mean MFA across all spacing treatments was comparable to a previous study on young South African-grown *P. patula* where the mean MFA varied between 7 and 29° along the first 16 annual rings from the pith (Wessels et al., 2015a). In that study the MFA values and trends of 30 *Pinus patula* trees from six sites were very similar to the 403 stems/ha treatment in our study. The trees from the mentioned study were planted at about 1372 stems/ha and were roughly of the same age and from the same region and thinned twice. The initial MFA in the first four tree rings of the 403 stems/ha treatment of our study was, as expected, higher than that of the earlier study which was planted at about 1372 stems/ha. After thinnings, however, MFA of the similar rings were comparable. This probably indicates that regular thinning, before severe competition commences, produces wood similar to that produced by very wide initial spacing and also demonstrates the potential of late or no thinning as a management tool to regulate MFA in wood. Overall a higher planting density clearly shows potential to decrease the average MFA and that of equivalent annual rings.

3.6 Density

Density results showed a highly significant interaction between ring number and spacing treatment (Table 6). The variation of density from pith to bark and for each spacing treatment level is illustrated in Figure 10. There were significant differences in density within the tree depending on the spacing treatment and the ring number from the pith.

Table 6: ANOVA table for density with ring from pith and spacing treatment as factors (shaded effects were significant at p<0.05

Source of variation	Num. DF	Den. DF	F	p
Spacing	3	36	1.2664	0.3005
Rings from pith	11	370	49.1116	<0.0001
Rings from pith*Spacing	33	370	2.4125	<0.0001

The mean annual density – the average for the entire ring, including earlywood and latewood – varied from around 370 kg/m^3 close to the pith to about 600 kg/m^3 at ring 10 (Table 4). There was no obvious difference in the mean annual density across all spacing treatments within the first six annual rings. Thereafter the mean annual density for the 403 stems/ha planting density treatment was significantly lower than the other treatments for most year rings. What was noticeable was that the density gradient from pith to ring 10 seems to decrease with planting density. The 403 stems/ha treatment had a much lower density gradient than the other treatments. In terms of wood quality a low density gradient is usually considered as a positive trait (Malan, 2010).

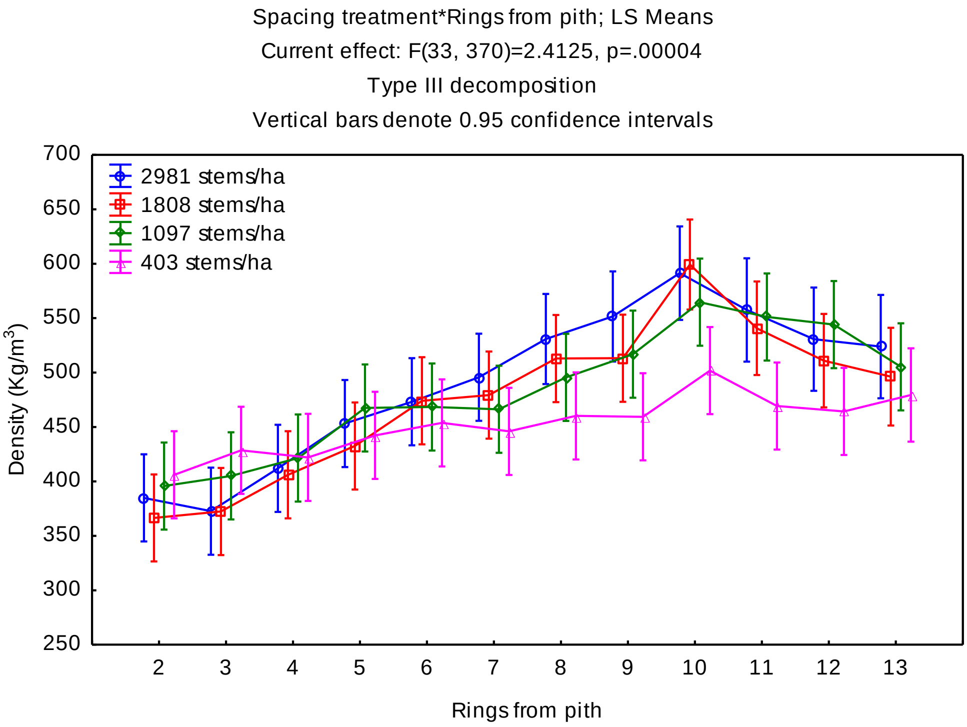

Figure 10: Variation in density at different spacing treatments and rings from pith. Vertical bars denote 95% confidence intervals.

Density generally increased up to ring 10 from where on it then gradually declined. A previous study on 16-20 year-old South African *P. patula* showed density at breast height to rapidly increase from pith to bark until about 600 kg/m^3 at the 16th annual ring without clearly declining at any point (Wessels et al., 2015a). According to Tsoumis (2009), the density profile of most softwoods is low values close to the pith which then rises to a characteristic level before declining at a "great" age. However, the decrease in density after year ring 10 was at an early age and consistent over all the planting densities and was possibly related to environmental factors. The per year ring density differences between treatments were much less pronounced than that of MFA. For both MFA and density the 403 stems/ha showed the biggest difference compared to other treatments.

3.7 Ring width

Analysis of variance for ring width showed a highly significant interaction between rings from pith and spacing treatment (Table 7). The variation of ring width from pith to bark and for each spacing treatment level is illustrated in Figure 11. There were significant differences in ring width within the tree depending on the spacing treatment and the ring number from the pith.

Table 7: ANOVA table for ring width with ring from pith and spacing treatment as factors (shaded effects were significant at p<0.05).

Source of variation	Num. DF	Den. DF	F	p
Spacing	3	36	18.8743	<0.0001
Rings from pith	11	370	283.2291	<0.0001
Rings from pith*Spacing	33	370	1.7622	0.0071

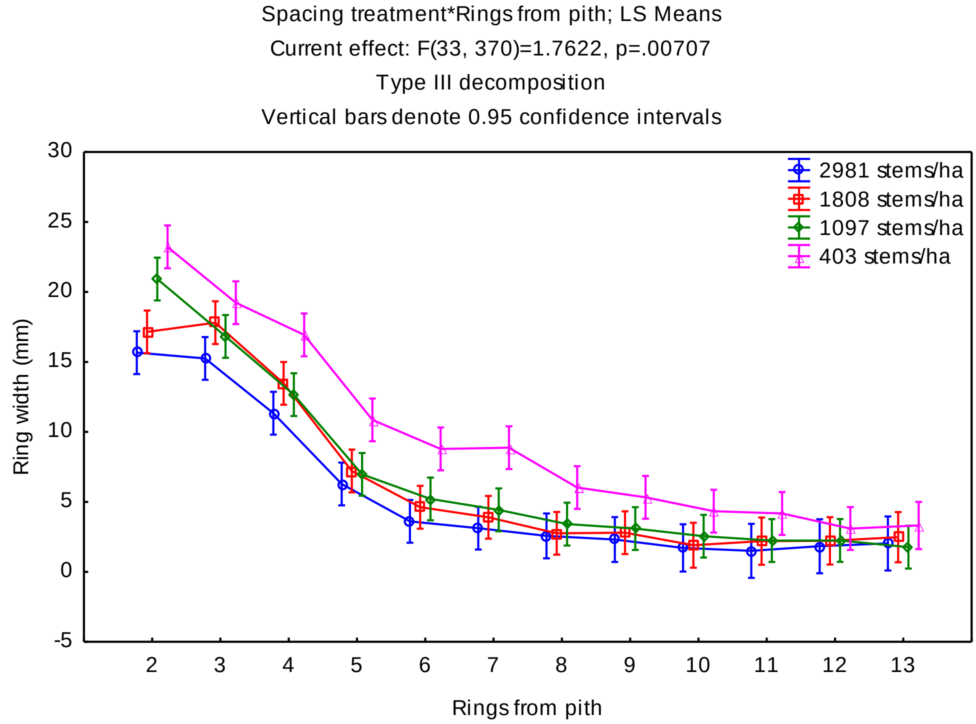

Figure 11: Variation in ring width at different spacing treatments and rings from pith. Vertical bars denote 95% confidence intervals.

The mean annual ring width varied from about 23 mm near the pith to about 2 mm at ring 13 (Table 4). At 403 stems/ha the mean annual ring width from the 2nd to 13th annual ring was about one to four mm more than at 1097 stems/ha. LSD post hoc tests reveal significant differences in ring width between 403 stems/ha and 1097 stems/ha up until the ninth year ring (Table 4). The last four annual rings were similar only differing by an average of 1.5 mm. With the exception of the second annual ring, no significant differences in ring width were found from pith to bark between 1097 stems/ha and 1808 stems/ha (Table 4). The same was true for the difference in ring width between 1808 stems/ha and 2981 stems/ha although the third annual ring showed a significant difference. As with MFA and density, the differences were most pronounced between 403 stems/ha and 1097 stems/ha.

Ring width is an important property since it affects the geometry of sawing and subsequently the individual board properties (Figure 12 – 15).

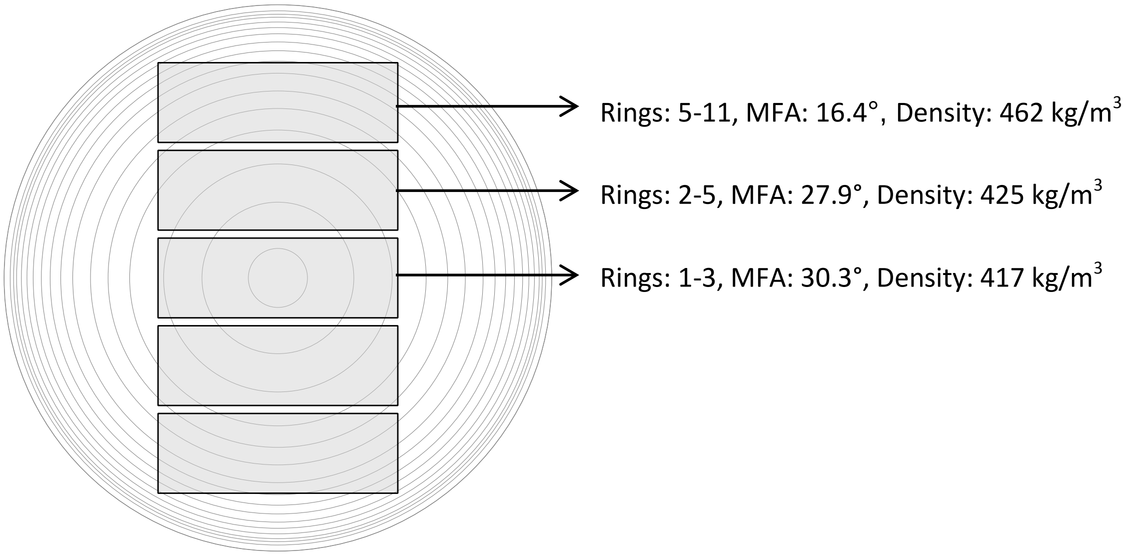

Figure 12: The mean ring widths for 403 stems/ha overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position with their mean MFA and density

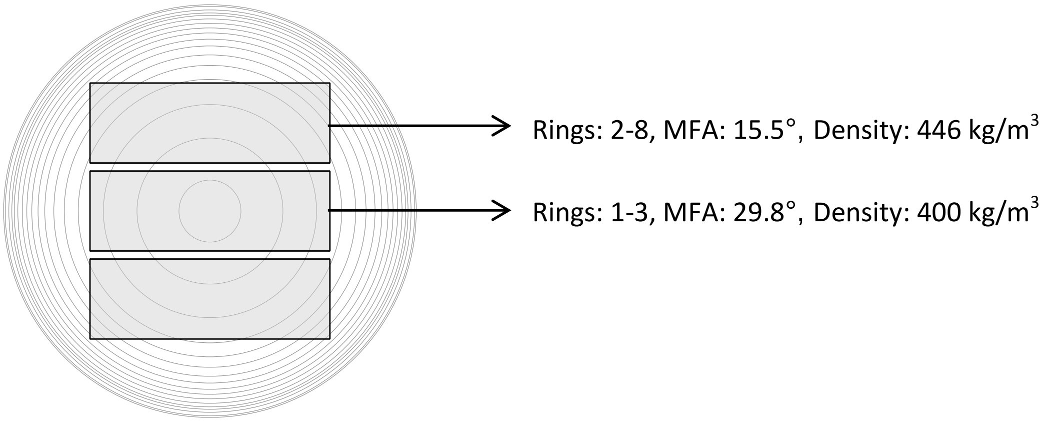

Figure 13: The mean ring widths for 1097 stems/ha overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position with their mean MFA and density

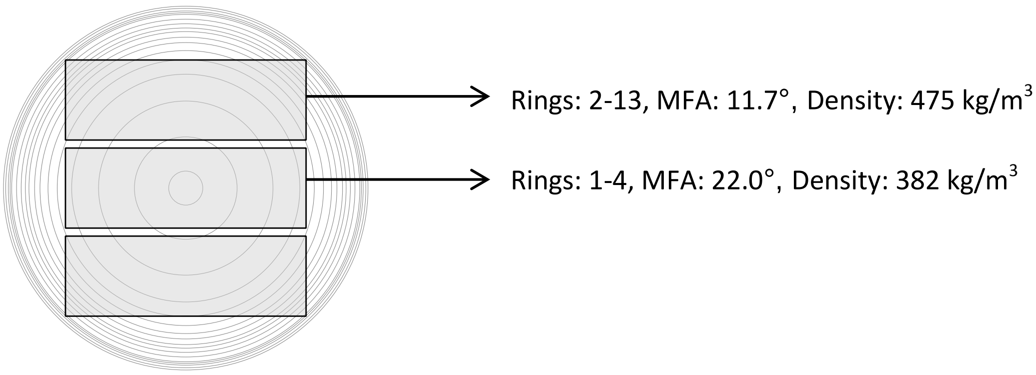

Figure 14: The mean ring widths for 1808 stems/ha overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position with their mean MFA and density

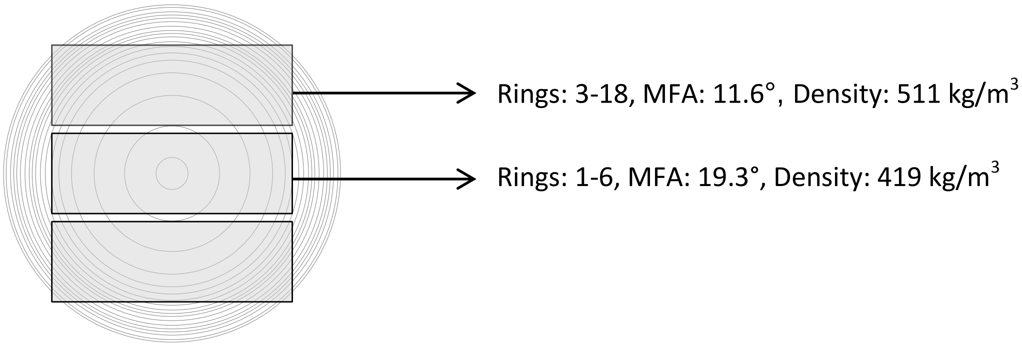

Figure 15: The mean ring widths for 2981 stems/ha overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position with their mean MFA and density

Figure 12– 15 shows the cross-sectional images with the mean ring widths per planting density treatment overlaid with a typical cant sawing pattern of 40 x 120 mm boards. For each board the mean density and mean MFA of the rings present in that board were calculated. In a study by Wessels et al. (2015) it was shown that the mean density and mean MFA calculated from year rings could be used to successfully predict the dynamic MOE of boards. The pith boards from the centre of the 403 stems/ha treatment had a maximum ring number of three in the board, whereas the pith boards from the 2981 stems/ha had maximum ring number of six. Since especially MFA improved significantly with ring numbers from the pith and in absolute terms for higher planting densities, it resulted in better MFA properties for similar board positions for higher planting density treatments. For instance, the pith boards of the 2981 stems/ha treatment had a mean MFA of 19.3° compared to the 403 stems/ha treatment, which had a mean MFA of 30.3°. Wood density showed a similar trend of increasing with board position and planting density treatment except for the density of the pith boards of the 403 stems/ha treatment, which was quite high due to the high density values of the first three rings from pith for this treatment.

In summary, the higher planting densities (1808 and 2981 stems/ha) gave three distinct advantages in terms of wood properties compared to the lowest planting density (403 stems/ha): Firstly, the absolute mean MFA values of higher planting densities were significantly lower for rings close to the pith. Secondly, based on MFA, the juvenile core seems to be restricted to the first seven to eight year rings from the pith, whereas for the 403 stems/ha treatment the juvenile core transition only started at rings 10 or 11. Thirdly, due to suppressed growth, the centre boards of higher planting densities will contain more mature rings than that of the 403 stems/ha. Combined, this resulted in centre boards of the 403 stems/ha having a mean MFA that was 57% higher than that of the 2981 stems/ha treatment. Wood density was less affected by planting density. On the other hand, the advantage with lower planting density is the faster diameter growth and subsequently additional boards that can be recovered from the sides of logs with relatively good MFA and density properties (see Figure 12). However, the mean MFA and density of the second board from the pith from the 403 stems/ha treatment was still higher than the mean of the first board next to the pith of the 2981 stems/ha treatment.

3.7 Relationships between properties

Table 8: Pearson correlation coefficients between the mean tree variables and wood properties measured or calculated from all 40 increment cores (shaded correlations were significant at p<0.05).

Variable	1	2	3	4	5	6	7
1. DBH	1.00	0.65	-0.86	0.81	-0.22	0.47	-0.51
2. Height		1.00	-0.24	0.51	0.08	0.27	-0.19
3. Slenderness			1.00	-0.65	0.25	-0.37	0.42
4. Ring width				1.00	-0.47	0.34	-0.39
5. Density					1.00	-0.08	0.23
6. MFA						1.00	-0.66
7. MOE_{fak}							1.00

Pearson correlations between the various tree variables and wood properties measured and calculated for individual trees are shown in Table 8. Note that these correlations were only between the 40 trees where increment cores were removed. Stem slenderness displayed significant relationships with all variables with the exception of density.

Density only displayed a significant relationship with ring width as smaller annual rings generally have higher proportions of latewood and consequently higher density. The average MFA (from pith to bark including all annual rings) displayed the strongest relationship with the mean MOE_{fak}. Even though stress wave velocity and consequently the calculated MOE_{fak} are only an indication of the outermost annual rings stiffness, the average MFA from pith to bark accounted for 44% of the variation in the mean MOE_{fak}. MFA is probably the mechanism through which the tree compensates for the instability caused by a high slenderness ratio. Density, on the other hand, did not correlate with slenderness at all and is probably only influenced by environmental and growth factors.

4. Conclusions

Based on the results from this study, the following conclusions were made:

- Stem curve displayed no clear trend from 403 stems/ha to 2981 stems/ha although it was highest on average for the 403 stems/ha treatment.

- DBH and height of young *P. patula* rapidly increased with a decrease in planting density. In comparison, DBH was much more severely influenced by planting density than height. The mean tree height was significantly higher for the 403 stems/ha than all the other spacing treatments. There was a highly significant effect of planting density on the slenderness ratio – which increased by 68% from 403 stems/ha to 2981 stems/ha.

- The dynamic MOE on standing trees (MOE_{fak}) increased by 48% from the 403 stems/ha treatment to the 2981 stems/ha treatment. This increase in dynamic MOE with higher planting densities was greater than found in other research studies on different species of softwoods where similar planting density ranges were examined.

- MFA was significantly influenced by both planting density and ring number and the interaction between them. The mean MFA at similar ring numbers decreased significantly from the 403 stems/ha toward the higher planting densities (1808 and 2981 stems/ha). There were no significant differences in MFA at similar ring numbers between the 1808 and 2981 stems/ha treatments.

- Planting density had a limited effect on wood density – a property which displayed no significant relationship with any variable except ring width.

- Virtual sawing of logs indicated that much lower mean MFA board values will be obtained at similar board positions for higher density stands compared to lower density stands. Board density from pith to bark was less pronounced than board MFA.

- There was a significant relationship between MFA and MOE_{fak} with a Pearson correlation (r) of -0.66 and between MFA and slenderness (r =-0.37). MFA is probably the mechanism through which the tree compensates for the instability caused by a high slenderness ratio. Density, on the other hand, did not correlate with slenderness at all and is probably only influenced by environmental and growth factors.

The results of this study showed that increased planting density has significant potential to improve the underlying wood properties controlling the lumber stiffness of *Pinus patula* trees. Future work should include destructive sampling of trees and processing into lumber to evaluate the effect of planting density on the actual final product. Stem form at the final harvest could possibly also be improved using higher planting density and thinning but results were not conclusive. More work is required to understand the effect of planting density on stem form and also the possible effect of thinning.

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Chapter 3

The effect of planting density on the MOE, MOR and other properties of young *Pinus patula* lumber

Abstract

A reduction in harvesting ages due to faster growth resulted in reduced stiffness of lumber from South African pine saw-log resources. The objective of this study was to evaluate the effect of planting density on the static modulus of elasticity (MOE_{edge}), modulus of rupture (MOR) and other important properties of young *Pinus patula* lumber. A total of 37 trees from two commercial compartments, planted at different densities, were processed into 71 logs, cant-sawed into lumber, and tested for MOE_{edge}, MOR, density, and warp. The first compartment was 18 years old, planted at 1334 stems/ha and thinned to 827 stems/ha at age 11 years. The second compartment was 17 years old, planted at 1667 stems/ha and was unthinned. Lumber from the 1667 stems/ha compartment had a mean MOE_{edge} of 8967 MPa compared to a mean MOE_{edge} of 7134 MPa for the 1334/827 stems/ha compartment. Based on this evidence and results from previous studies, it seems as if planting density has a large effect on the stiffness of young *Pinus patula* lumber. The characteristic MOR for the 1667 stems/ha compartment (20.8 MPa) was much higher than that of the 1334/827 stems/ha compartment (12.1 MPa). Density and warp properties were sufficient for structural grade lumber. Results from this study suggest that increased planting density may have a very positive effect on some lumber properties of young *Pinus patula* trees.

Keywords: *Modulus of elasticity; Modulus of rupture; Pinus patula; planting density; wood density*

1. Introduction

The lack of suitable and available land for afforestation in South Africa has seen the focus of softwood plantation management move towards accelerated tree growth through tree breeding efforts and improved silvicultural practices and management techniques (Malan, 2003). This strategy has been implemented to supply the country's growing need for lumber and to reduce the cost per unit of lumber produced (du Toit et al., 2010; Wessels et al., 2014). The rapid growth enables plantations to adopt shortened rotations as trees produce log classes of merchantable sizes sooner (Cown 1992; Downes et al., 2002). The mean age of saw-log plantations in South Africa has dropped from 14.14 years in 1983 to 11.25 years in 2003 (Crickmay and Associates, 2005). Considering the mean age to be typically half that of the harvesting age, the rotation age was then reduced from around 28 years in 1983 to less than 23 years by the end of 2003.

The aim of these short-rotation systems is usually to maximize volume yields by increasing site productivity for obvious financial gains with less concern for important properties regarding wood quality. The resulting saw-logs entering the market from these short rotation plantations contain a considerable proportion of juvenile wood also referred to as corewood (Cown, 1992). The properties of corewood are highly variable and considered inferior to that of mature wood and also affect the performance of structural lumber (Malan, 2010).

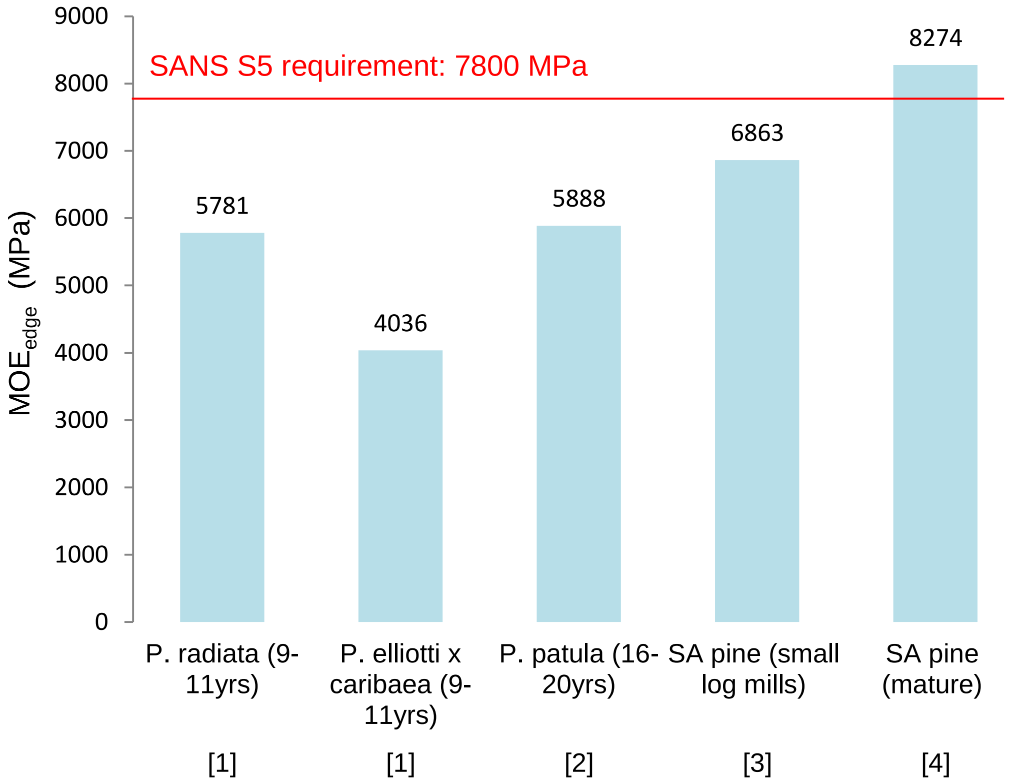

Figure 1: Mean MOE of various SA Pine lumber (From the following studies: [1] Wessels et al. (2011), [2] Dowse and Wessels (2013), [3] Wessels and Froneman (2012), [4] Crafford and Wessels (2011))

Burdzik (2004) initially suspected a loss of grade strength of South African pine. Visually graded S5 lumber from four sawmills in South Africa was chosen to be representative of "forestry areas with low-density SA pine" in his study. The results showed that all of the mills produced graded lumber, which did not conform to the bending strength or stiffness requirements of SANS 10163-1 (2003). More recent studies supported concerns that the wood material of the various South African forest resources has changed and has had a negative impact on mechanical properties, specifically the MOE of lumber (Figure 1). Note that the reported means in Figure 1 consist of the full sample including rejected lumber due to defects. For users of structural lumber it is important that the strength and stiffness properties of a given lumber resource produce a high proportion of lumber conforming to minimum requirements according to the guidelines of SANS 10163-1 (2009).

In SA, structural lumber is predominantly used in roof trusses where the mechanical properties influence the performance of wood as building material. The issue of low stiffness lumber requires attention since about 75% of the total sawn wood produced is sold and used as structural lumber and other building components (Crickmay and Associates, 2015).

Possible ways to address the low stiffness may include the following with the last point being the focus of this study:

1. Incorporate the selection of high-stiffness parent trees in tree breeding programs.
2. Apply appropriate structural grading rules and design values according to the available resource's current characteristics i.e. lower the structural grade requirements.
3. Improve the forest resource through the introduction new species and hybrids
4. Improve the forest resource through alternative silvicultural management such as using higher planting densities.

The potential improvement of forest resources through increased planting densities has been widely investigated in the last decade with many yielding promising results (Lasserre et al., 2005; Roth et al., 2007; Waghorn et al., 2007; Lasserre et al., 2009) The objective behind higher planting densities is to encourage the development of more slender trees, which in turn produce higher stiffness wood to prevent buckling or bending failure of the stem due to an increase in the tree's self-weight and wind loading. Froneman (2014) reported the mean MOE of *P. elliottii* lumber to significantly improve with higher planting densities. *P. radiata,* however, did not display the same positive response but its MOE was already relatively high at the normal South African saw-log planting density. High planting densities may therefore be a useful management technique for growers and processors of trees interested in producing structural lumber in order to encourage stiffer wood, particularly during juvenile growth (Wessels et al., 2015a).

The main objective of this study was to evaluate the effect of planting density on the static MOE, MOR and other important properties of young South African-grown *P. patula* lumber.

2. Materials and methods

2.1 Experimental layout

The study was conducted using two commercial compartments of 17 and 18 year-old *Pinus patula* trees located in the Mpumalanga escarpment at the Montrose plantation near Barberton. The ideal would have been to destructively sample a spacing trial where a wide variety of different planting density treatments could be evaluated. However, at the time no *Pinus patula* spacing trials were available in South Africa for destructive testing, and so commercial compartments had to be used. The selected plots were located close to each other and were planted at 1334 stems/ha and 1667 stems/ha respectively. The compartment planted at 1334 stems/ha was thinned to 827 stems/ha at 11 years of age while the compartment planted at 1667 stems/ha had a stand density of 1560 stems/ha at the time of sampling (see Table 1). Results from a previous study on the MOE of *P. patula* lumber from the Mpumalanga escarpment were also available for comparison purposes (Wessels et al., 2014).

Table 1: General data for each compartment

Compartment	Age (yrs)	Espacement (m)	Initial stems/ha	Thinning age:	Final stems/ha	Number of trees sampled	Mean DBH (cm)	Mean Height (m)
C40a*2	18	3 x 2.5	1334	11	827	20	29	23.8
C34*2	17	3 x 2	1667	-		17	27.4	19.8

It must be emphasized that the planting density of both sample compartments were higher than the norm for *Pinus patula* saw-log plantations in South Africa, which are usually planted closer to a 1000 stems/ha. Also the thinning age of 11 years for compartment C40 was later than the norm for *Pinus patula* from this area, which would normally be thinned around 7 or 8 years.

This area receives about 672 mm of rain per year with average midday temperatures ranging from 20.2°C in June to 26.8°C in January. The two sample compartments had been selected mainly due its difference in planting density and also close proximity to each other.

Both compartments were pruned during the fifth, seventh and ninth year to 2 m, 3.5 m and 5.5 m respectively. Only trees with a DBH greater than 23cm were included in the study.

2.2 Measurements

Twenty trees from compartment C40 and 17 from compartment C34 – thus a total of 37 trees were considered. During harvesting two logs were sampled (where possible) from 37 trees producing 71 logs which were then processed into 260 boards for further analysis. Discs were also sampled up to 7.9 m as shown in Figure 2. Templates were applied to log ends in field soon after felling and before transportation to the sawmill (Figure 3). These templates had a grid on it including the number of the tree which made it possible to track any board produced to the position in the log, the specific log, the specific tree and the compartment from which it was produced.

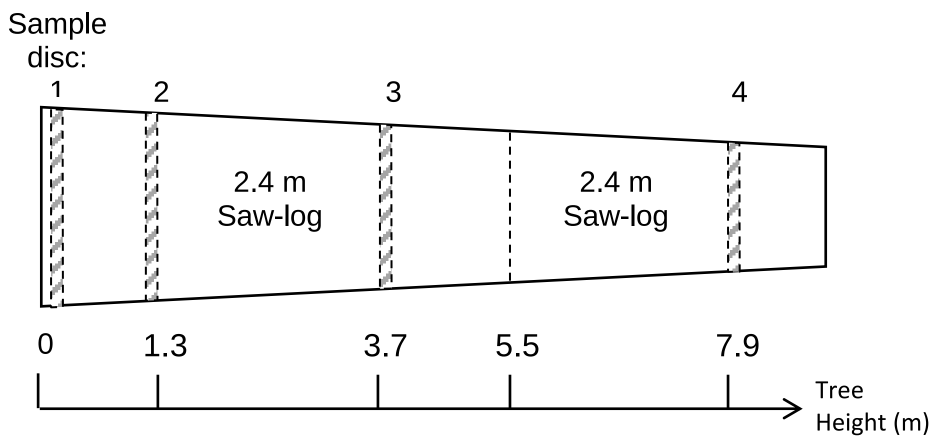

Figure 2: Sample discs and log position

The logs were then transported to and processed at a local sawmill where a cant sawing pattern was used. All lumber had cross-sectional wet dimensions of 40 x 120 mm (Figure 4). Boards were kiln-dried to a target moisture content of 12%. Logs were reconstructed using the portions of the templates attached to board ends prior to any mechanical tests on the lumber. Boards were numbered from the pith outwards. For all reconstructed logs it was possible to locate the last latewood produced before felling as sections where small portions of wane were still visible. It was thus possible to determine the exact year (real age) when a specific annual ring in a board was produced.

Figure 3: Templates applied to log ends

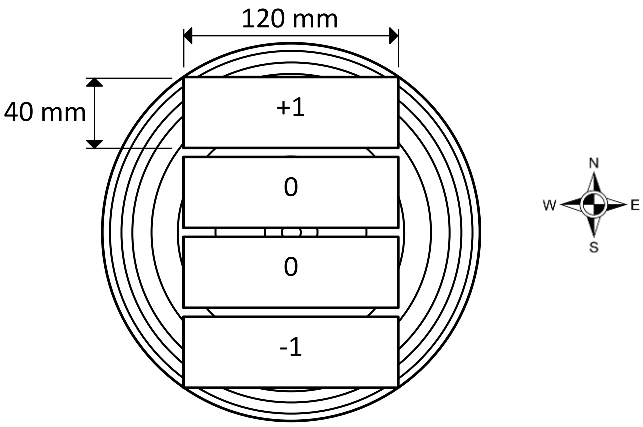

Figure 4: Sawing pattern used

The ring number from pith indicates the cambial age. For each board, the mean, minimum and maximum cambial age was determined by numbering annual rings on reconstructed log ends and counting those contained in individual boards (Figure 5). In the same way, a value could be assigned to each board indicating the mean, minimum or maximum real age of annual rings present in the board based solely on board ends. The ring width, defined as the perpendicular distance from the start of earlywood to the end of latewood, was also measured (Figure 5).

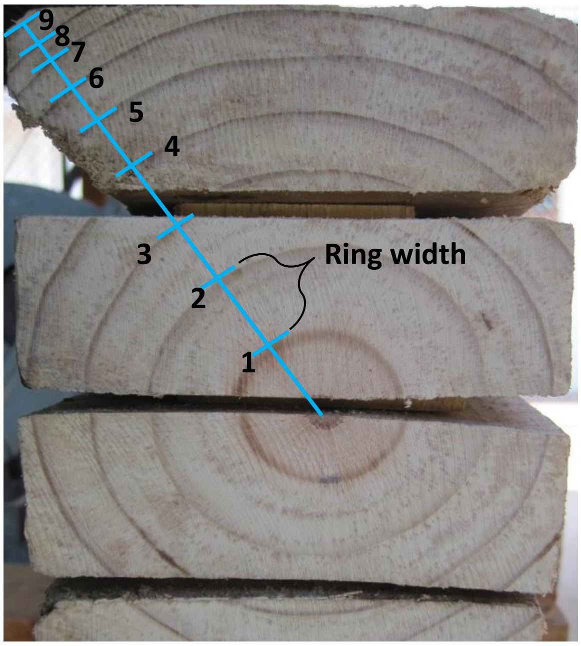

Figure 5: Sanded board ends. Cambial age and ring width measurements

The mean, minimum and maximum ring widths were determined. Only full annual rings on board ends were considered for the cambial age and ring widths. All boards containing pith tissue were marked as board “0” – pith boards. Boards adjacent to these pith boards were labelled board “1”. In most cases, the two centre boards both contained pith tissue and were both marked as pith boards. All 260 boards were visually stress graded by an accredited grader. Density, MC and Warp (twist, bow and spring) of each board was measured according to SANS 1783-1 (2009) (Figure 6).

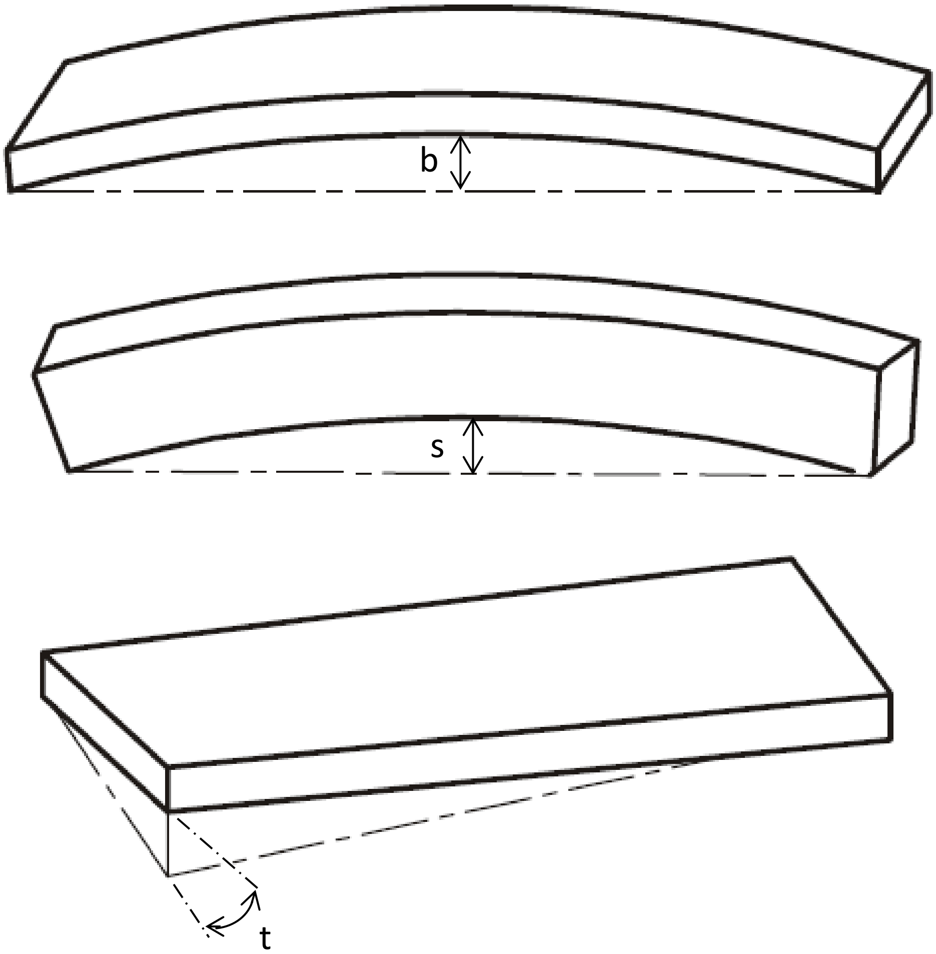

Figure 6: Determination of warp: bow in mm/m (b), spring in mm/m (s), and twist in degrees (t).

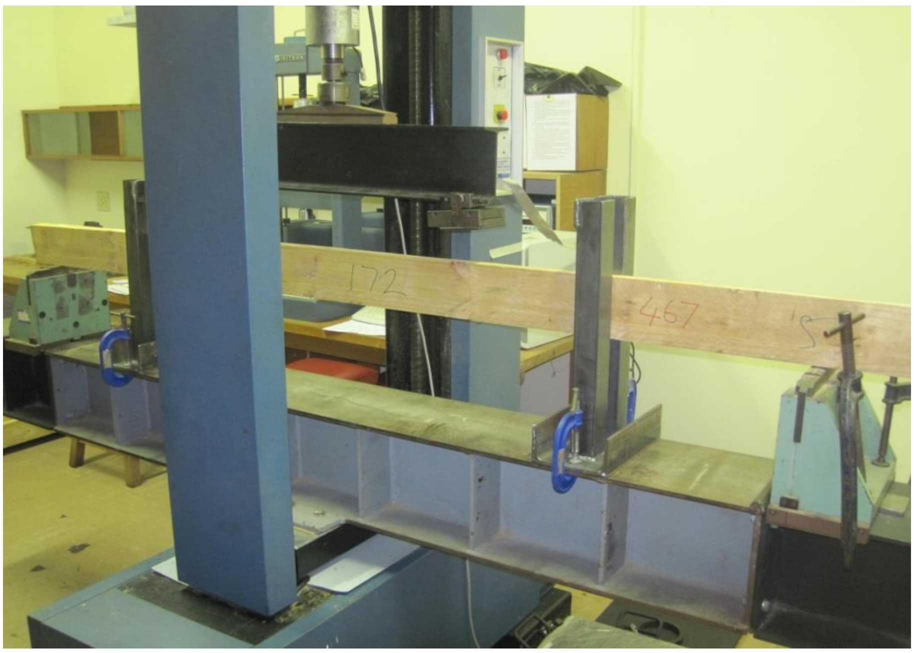

Figure 7: Edgewise 4-point bending test setup

Four-point bending tests were performed according to the guidelines set out in SANS 6122 (2008) (Figure 7). A test speed of 25 mm/min was applied as previous investigations by Crafford and Wessels (2011) showed good correlations between faster test speeds than the prescribed speed of between 7 and 14 mm/min. The MOE_{edge} was calculated using a 4-point setup between the loads 400 N and 2200 N. The load range was slightly adjusted for an instance where the load-deflection curve was not completely linear.

2.3 Data analysis

Mixed model repeated measures ANOVA's were done using compartment, log position and board position as factors. The effect of these factors was analysed on MOR, MOE, density and warp. Basic statistics were conducted using R (R Core Team, 2014) with the main analysis done in Statistica (Dell Inc, 2015). Where a factor was not included in any significant interactions, the main effect of the factors on the dependent variables were interpreted otherwise significant interactions were graphed and interpreted. Datasets for each analysis were visually inspected for normality and formally tested for homoscedasticity (Levene's test).

3. Results and discussions

The measurements on all sawn boards separated according to compartment (stems/ha), log position and board position can be seen in Table 2. Note that data missing in this table indicates that too few values were available for a specific dataset. This was mostly the case for the fifth percentile bending strength and MOE_{edge} where a relatively large sample (+40) is typically required. The Pearson correlations (r) between variables can be seen in Table 3.

Table 2: Summaries for the mean values of measured properties for all boards. Data for the few board 2 position was not included individually but in the "All boards" column

Description		SANS visual grade	Compartment C40 (1334/827 stems/ha)					Compartment C34 (1667 stems/ha)					All boards	SANS 1783-2 SANS 10163-1 Min/max requirements/ limits
			Bottom log		Top log		All	Bottom log		Top log		All		
			Board 0	Board 1	Board 0	Board 1		Board 0	Board 1	Board 0	Board 1			
No. of boards (n)		All	33	38	34	33	141	30	32	24	32	119	260	
Cambial age	min	All	1.2	3.2	1.2	3.5	2.3	1.2	3.7	1.2	3.4	2.5	2.4	
	mean	All	3.3	6.7	3.6	7.2	5.3	4	7.8	4.1	6.9	5.7	5.6	
	max	All	5.3	10.3	6.1	11	8.3	6.7	11.8	7	10.5	9.2	8.7	
Real age	min	All	2.7	5.1	4.4	7.3	4.9	2.7	5.8	4.8	7.8	5.4	5.1	
	mean	All	5.0	8.7	7.2	11.1	8.1	5.7	9.8	8.0	11.4	8.8	8.4	
	max	All	7.4	12.3	9.9	14.8	11.2	8.7	13.8	11.3	15.0	12.3	11.7	
Ring width	min	All	5.3	3.9	4.8	3.6	4.4	4.5	3.6	4.9	4.3	4.3	4.3	
(mm)	mean	All	10.9	7.1	9.5	6.6	8.4	9.0	6.3	8.7	7.2	7.7	8.1	
	max	All	20.5	13.0	16.8	11.6	15.3	16.1	10.7	13.2	10.6	12.5	14.0	
Density (kg.m^{-3})		All	408	457	418	448	435	464	521	461	501	490	460	360 (S5)
Bow (mm/m)		All	2.0	1.7	1.5	1.4	1.6	2.2	1.6	1.6	1.2	1.7	1.6	10
Twist (°)		All	1.6	1.6	1.9	1.7	1.7	1.9	2	2.4	1.9	2	1.9	4-5
Spring (mm)		All	1.5	0.5	0.7	0.7	0.6	1.2	0.7	0.9	0.7	0.8	1.7	15
MOE_{dyn} (MPa)		All	5619	8800	6746	8910	7599	7694	11530	8244	10582	9635	8537	

Table 2: Continued

Description	SANS visual grade	Compartment C40 (1334/827 stems/ha)					Compartment C34 (1667 stems/ha)					All boards	SANS 1783-2 SANS 10163-1 Min/max/ requirements/ limits
		Bottom log		Top log		All	Bottom log		Top log		All		
		Board 0	Board 1	Board 0	Board 1		Board 0	Board 1	Board 0	Board 1			
MOE_{edge} (MPa)	All	5507	8171	6376	8117	7134	7730	10460	7798	9420	8967	7973	
	xxx			5834		6017					8953	6343	
	S5	5550	6581	6346	7438	6274	6921		7654	8808	7655	6805	7800
	S7		8844		8303	8455	8498		8346	9286	8783	8619	9600
	S10		9319		8968	9228		11028		10370	10772	10202	12000
	S5-10					7201					8967	8031	
5^{th} percentile MOE_{edge} (MPa)	All					4214					5832	4639	
	xxx												
	S5					3939					5832	4433	4630
	S7											6016	5700
	S10											7063	7120
	S5-10					4433					5832	4760	
5^{th} percentile MOR (MPa)	All					12.1					20.8	13.9	
	xxx												
	S5					10.6					15.5	12.1	11.5
	S7											20.1	15.8
	S10											23.7	23.3
	S5-10					12.1					20.8	14.1	

Table 3: Pearson's correlation coefficients (r) between all board variable means. Marked correlations are significant at $p<0.05$.

Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. MOE_{edge}	1.000	0.948	0.834	0.744	0.604	0.524	-0.278	-0.616	-0.529	-0.090	-0.003	0.047
2. MOE_{dyn}	-	1.000	0.799	0.798	0.676	0.620	-0.292	-0.678	-0.569	-0.119	0.057	0.015
3. MOR	-	-	1.000	0.596	0.455	0.371	-0.176	-0.491	-0.388	-0.024	-0.010	-0.020
4. Density	-	-	-	1.000	0.515	0.471	-0.159	-0.511	-0.387	-0.002	0.001	-0.114
5. Mean cambial age	-	-	-	-	1.000	0.874	-0.392	-0.811	-0.717	-0.102	-0.023	0.054
6. Mean real age	-	-	-	-	-	1.000	-0.345	-0.806	-0.652	-0.161	-0.003	0.057
7. Min ring width	-	-	-	-	-	-	1.000	0.348	0.847	0.049	-0.058	-0.089
8. Max ring width	-	-	-	-	-	-	-	1.000	0.732	0.135	-0.103	-0.070
9. Mean ring width	-	-	-	-	-	-	-	-	1.000	0.106	-0.050	-0.073
10. Bow	-	-	-	-	-	-	-	-	-	1.000	-0.033	-0.062
11. Twist	-	-	-	-	-	-	-	-	-	-	1.000	-0.041
12. Spring	-	-	-	-	-	-	-	-	-	-	-	1.000

3.1 MOE$_{edge}$

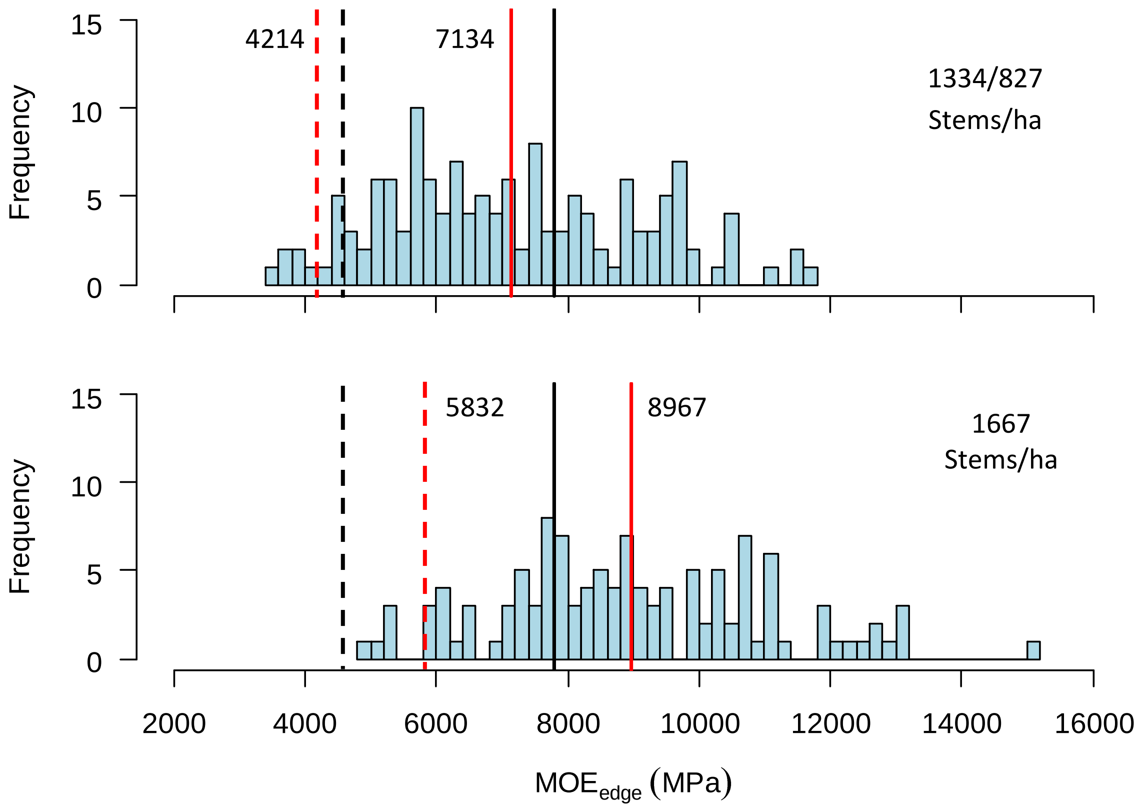

Figure 8: MOE$_{edge}$ distribution for each compartment. Black lines indicate required SANS S5 MOE mean at 7800 MPa (solid) and fifth percentile at 4630 MPa (broken). Red lines indicate sample means (solid) and fifth percentiles (broken).

The mean MOE$_{edge}$ of the 1667 stems/ha of 8967 MPa was 15% higher than the 7800 MPa required for structural lumber. On the other hand, the mean MOE$_{edge}$ of the 1334/827 stems/ha compartments of 7134 MPa was 9% lower than required for structural lumber (Figure 8). Even when excluding the visually graded non-compliance lumber, labelled “XXX” – which is typically rejected due to reduced strength as well as cosmetic defects – the mean MOE$_{edge}$ for the 1334/827 stems/ha compartment (7201 MPa) was still less than required for the lowest grade S5 (Table 2). The individual structural grades for the 1667 stems/ha compartment also did not comply with their respective requirements (Table 2), but the full sample excluding (or even including) XXX lumber was more than required for grade S5 lumber. This mixing of grades is typically the case in South African sawmills where all structural lumber is graded into the lowest grade S5 (Wessels et al., 2011).

It must be noted that the mean MOE$_{edge}$ of lumber from both the compartments sampled was higher than the norm for saw-log compartments of this age. In a study by Wessels et al.

(2014) on 16-20 year-old *Pinus patula,* which was planted at standard saw-log regime densities and thinned up to three times, a mean MOE_{edge} of 5755 MPa was obtained. The mean MOE_{edge} of the 1334/827 stems/ha compartment in this study was 24% higher and the 1667 stems/ha compartment was 56% higher than the results in the Wessels et al. (2014) study. Based on these comparisons it seems as if higher planting densities, combined with late or no thinning, have the potential to significantly increase the stiffness of *Pinus patula* sawn lumber. It must be noted though that growth site and the genetic material could also have had an influence in the differences in results.

The stiffness results of each compartment in terms of its 5th percentile MOE_{edge} were consistent with that of the mean MOE_{edge}. The 5th percentile MOE_{edge} for the 1667 stems/ha compartment – 5832 MPa – was 26% greater than the required minimum of 4630 MPa. Note that this value was even sufficient for grade S7 lumber (Table 2). In contrast, the 1334/827 stems/ha compartment MOE_{edge} 5th percentile was 9% lower than required (Figure 8). As with the mean MOE_{edge}, excluding xxx lumber did not sufficiently improve the 5th percentile (Table 2).

A three-way analysis of variance indicated no significant three-way interaction between compartment, log position and board position (Table 4). A significant interaction existed between log position and board position and between compartment and log position. As only four boards made up “board 2” they were omitted as a factor level from any statistical analysis. Both board position and compartment had a significant effect on MOE_{edge}.

Table 4: A three-way analysis of variance for MOE_{edge} (MPa). Significant factors at the 5% level are shaded.

Source of variation	SS	Degrees of freedom	MS	F	P
Board position	3.02E+08	1	3.02E+08	117.81	0.0000
Compartment	2.06E+08	1	2.06E+08	80.43	0.0000
Log position	9.73E+04	1	9.73E+04	0.04	0.8457
Board position * Compartment	1.14E+04	1	1.14E+04	0.00	0.9470
Board position * Log position	1.62E+07	1	1.62E+07	6.33	0.0125
Compartment * Log position	1.26E+07	1	1.26E+07	4.90	0.0278
Board position * Compartment * Log position	1.34E+05	1	1.34E+05	0.05	0.8192
Error	6.36E+08	248	2.56E+06		

The influence of board position and log position on MOE_{edge} can be seen in Figure 9. A clear increase in MOE_{edge} from the pith boards to the adjacent boards is shown. This trend corresponds to the sharp increase in MOE from pith to bark found by other studies (Tsehaye et al., 1995; Xu and Walker, 2004; Antony et al., 2012). Fisher’s LSD test revealed no significant difference in MOE_{edge} between the pith boards of the bottom log and the pith boards of the top logs. The same was true for the outer boards. This is in agreement with a study by Wessels et al. (2014) who, in addition, found the 2nd boards from the bottom logs (with a mean cambial age of 8.1) to have significantly higher dynamic MOE than 2nd boards from the top logs and reasoned it to possibly be an effect of pruning on the 2nd boards of the top log. In this study the highest values were from the 1st boards from the bottom logs, which had a mean real age of 8.7 and 9.8 years respectively, which then should also have been partially free from knots given the pruning dates. The radial position of boards therefore clearly has more influence on MOE than longitudinal position which is in agreement with previous research (Xu and Walker, 2004; Wessels et al., 2014).

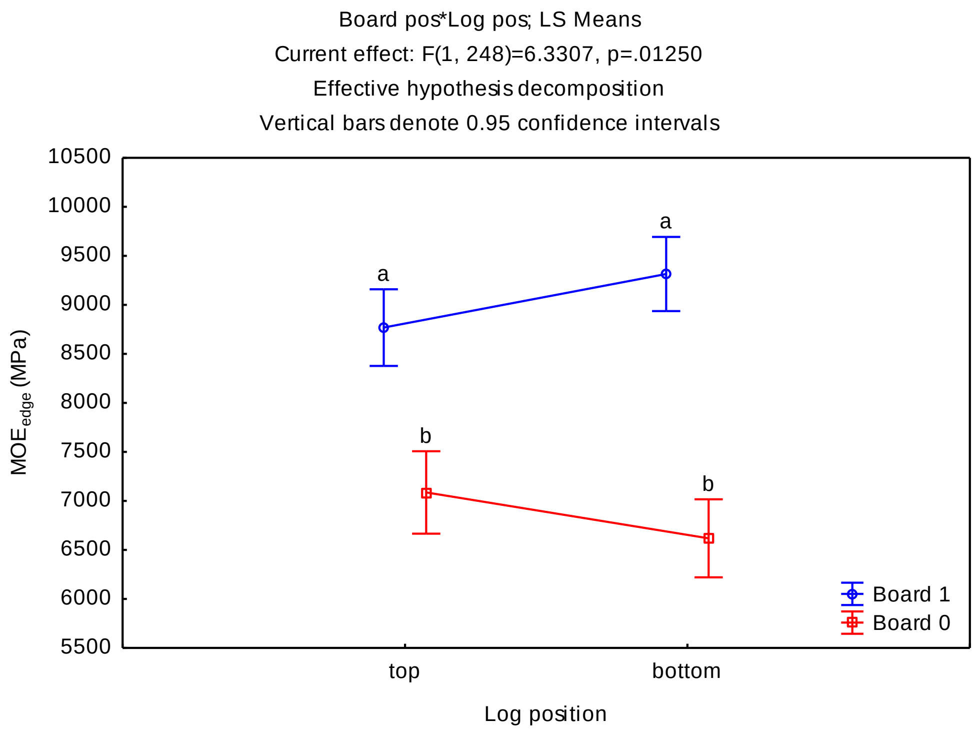

Figure 9: Means and 95% confidence intervals of MOE_{edge} of different board positions from the top and bottom logs. Different letters denote significant differences

The influence of log position and compartment on MOE_{edge} can be seen in Figure 10. A clear increase in MOE_{edge} from the 1334/827 stems/ha compartment to the 1667 stems/ha compartment is shown. There were no significant differences between the top and bottom log. The increase in MOE for the higher initial stems/ha is consistent with previous research (Waghorn et al., 2007; Froneman 2014).

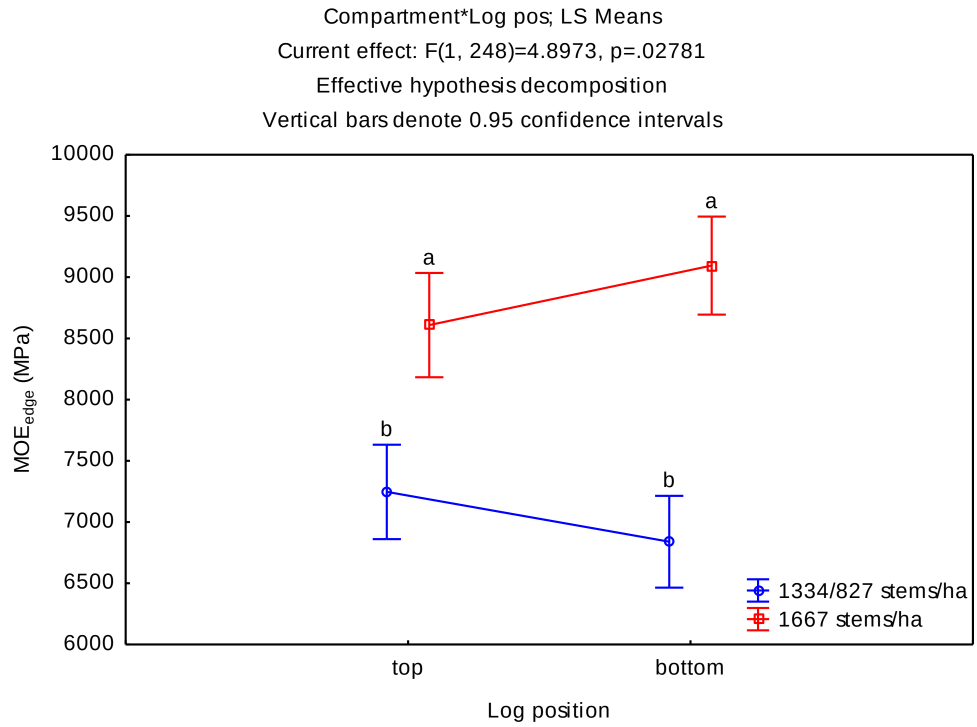

Figure 10: Means and 95% confidence intervals of MOE_{edge} of different compartments from the top and bottom logs. Different letters denote significant differences

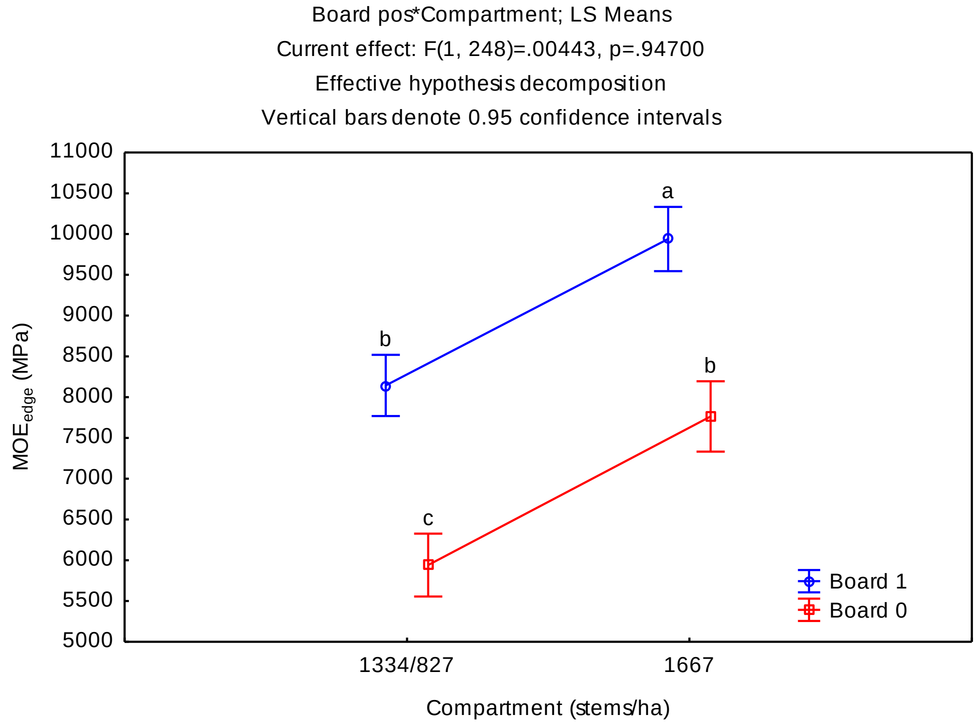

Figure 11: Means and 95% confidence intervals of MOE_{edge} of different compartments from the top and bottom logs. Different letters denote significant differences

The thinning event at 11 years on the 1334/827 compartment probably did not have a large influence on the MOE_{edge} of lumber. The mean minimum and maximum real age of the pith boards from this compartment were 2.7 and 7.4 years respectively for the bottom log and 4.4 and 9.9 years for the top log (Table 2). The wood in the pith board was, therefore, already formed by the time of the thinning at 11 years. For the bottom log's 1st board wood was formed from 5.1 to 12.3 years and for the top log 7.3 to 14.8 years. It is, therefore, possible that especially the top log's 1st board position could have been influenced by the thinning. However, there was very little difference in MOE_{edge} of the 1st boards from the bottom and top log of this compartment. There was, therefore, little evidence of a thinning effect. A detailed study on the MFA and density at ring-level will be a better way to quantify the possible effects that thinning may have on wood quality.

The higher planting densities clearly increased the proportion of lumber with stiffness values above the required 7800 MPa. The MOE of lumber at similar distances from the pith were increased significantly from 1334/827 stems/ha to 1667 stems/ha (Figure 11). Furthermore, the MOE of the pith boards from the 1667 stems/ha compartment was similar to that of outer boards for 1334/827 stems/ha compartment.

The higher MOE_{edge} values for the 1667 stems/ha compartment compared to the 1334/827 stems/ha compartment at similar board positions was probably due to several reasons. Firstly the slower growth resulted in similar board positions having older year rings in the 1667 stems/ha compartment. For instance board 0 of the bottom log of the 1334/827 stems/ha compartment had a maximum cambial age of 5.3 years compared to 6.7 years for the 1667 stems/ha compartment (Table 2). It is well established that density and MFA increase with year rings from the pith and therefore it will follow that the 1667 stems/ha boards with older more mature rings will have higher average density and MFA values. This argument is supported by the higher mean density value results for the 1667 stems/ha compartment at all the similar board positions (Table 2). Secondly, other studies also found that the absolute MFA values for more densely planted trees were lower at similar year rings than less densely planted trees (Lasserre et al., 2009). The lower MFA is probably due to increased slenderness of trees and the subsequent instability of the stem.

3.2 Bending strength (MOR)

The mean MOR was not included in Table 2 as only the characteristic or fifth percentile MOR value is relevant to designers of lumber structures. The combined 5th percentile MOR value for both the 1334/827 stems/ha compartment (12.1 MPa) and the 1667 stems/ha compartment (20.8 MPa) was higher than that required for S5 structural lumber. However, when separating the boards into different grades the results showed the 5th percentile for grade S5 lumber from the 1334/827 stems/ha compartment to be less than required by SANS 10163-1(2009) (Table 2). Only if all the structural grades (S5, S7 and S10) are considered as one structural grade, excluding the non-compliance grade XXX does the fifth percentile for 1334/827 stems/ha compartment exceed the requirement (Figure 12 and Table 2). In this case, even the inclusion of XXX boards did not change the characteristic value as there were very few of these boards. The 5th percentile for grade S5 lumber from the 1667 stems/ha compartment, 15.5 MPa, was fairly higher and much closer to the grade S7 requirement (Table 2)

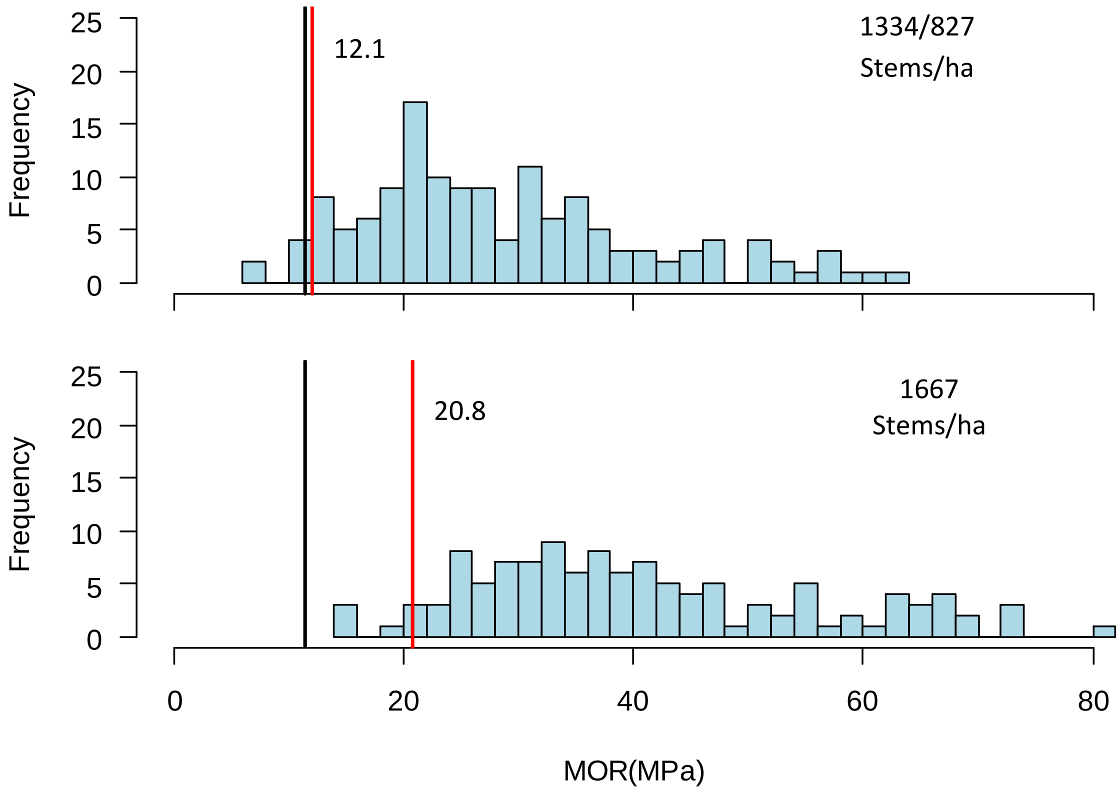

Figure 12: Distribution of MOR for each compartment. Black lines indicate required SANS S5 MOR fifth percentile at 11.5 MPa. Red lines indicate sample fifth percentiles

A three-way analysis of variance indicated no significant three-way interaction between compartment, log position and board position (Table 5). A significant interaction existed between log position and board position. Second boards were again omitted from any statistical analysis. Both board position and compartment had a significant effect on MOR.

Table 5: A three-way analysis of variance for MOR (MPa). Significant factors at the 5% level are shaded.

Source of variation	SS	Degrees of freedom	MS	F	P
Board position	7974.1	1	7974.1	56.396	0.000000
Compartment	9304.7	1	9304.7	65.806	0.000000
Log position	125.2	1	125.2	0.885	0.347686
Board position*Compartment	98.6	1	98.6	0.698	0.404418
Board position*Log position	1699.7	1	1699.7	12.021	0.000620
Compartment*Log position	450.2	1	450.2	3.184	0.075595
Board position*Compartment*Log position	112.4	1	112.4	0.795	0.373409
Error	35066.4	248	141.4		

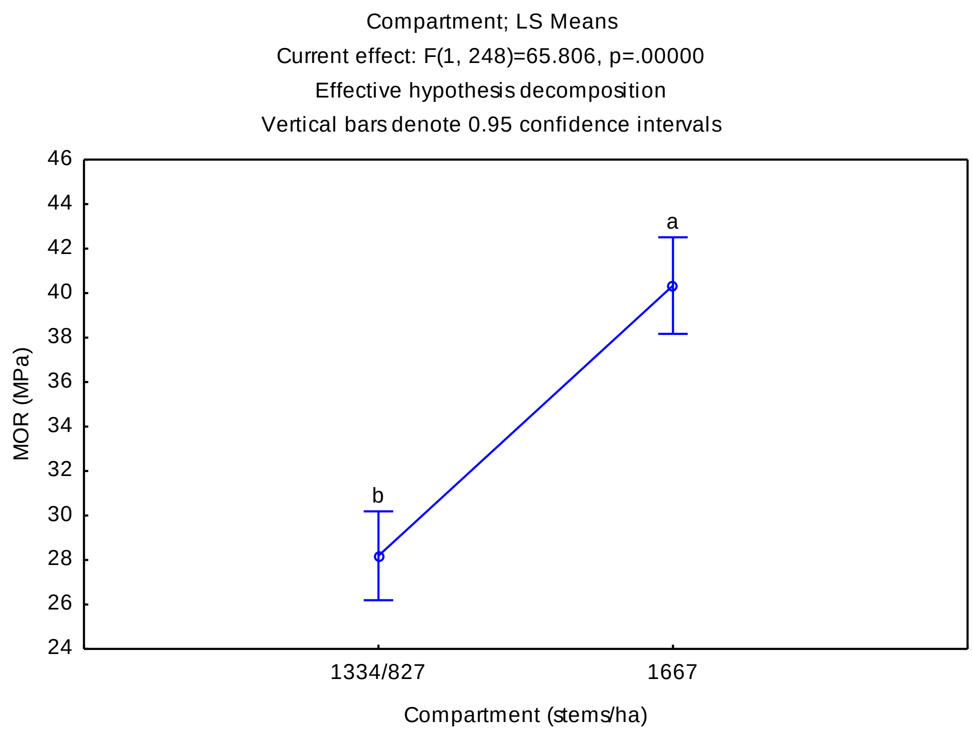

Figure 13: Means and 95% confidence intervals for MOR of different compartments. Different letters denote significant differences

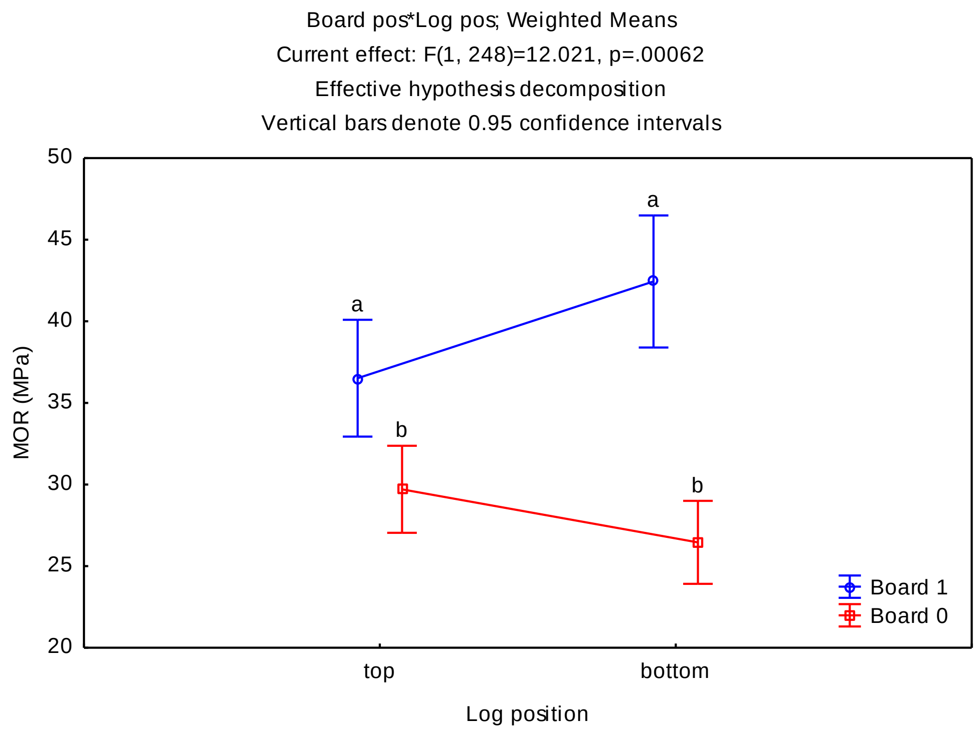

Figure 14: Weighted means and 95% confidence intervals for MOR of different board positions for the top and bottom logs. Different letters denote significant differences

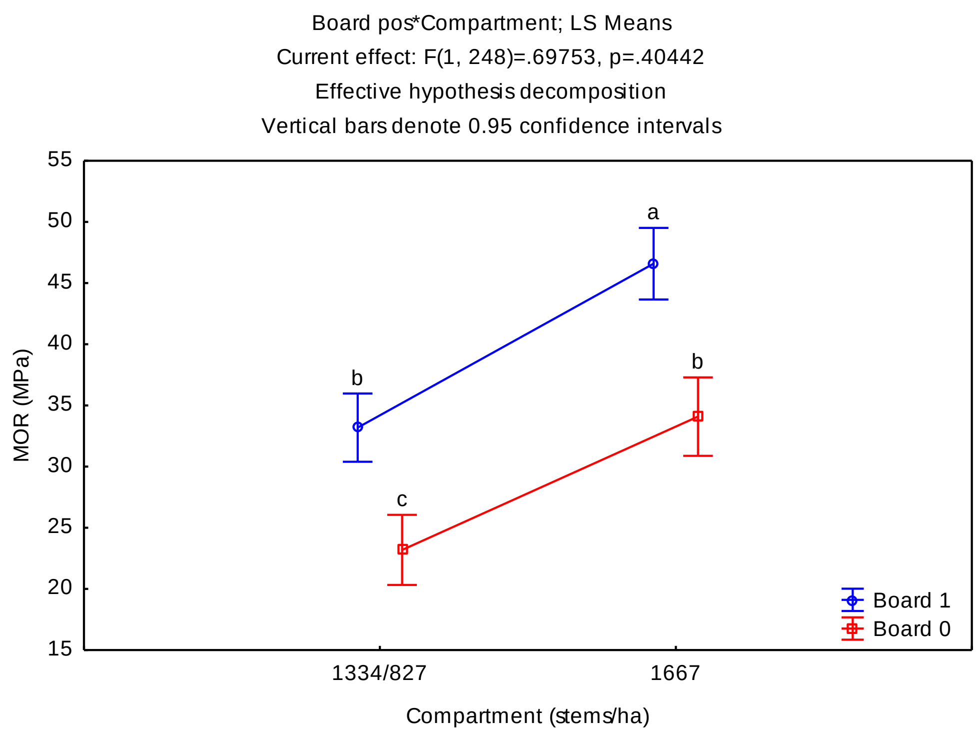

Figure 15: Weighted means and 95% confidence intervals for MOR of different board positions for 1334/827 stems/ha and 1667 stems/ha. Different letters denote significant differences

The mean MOR was much higher for the denser planted compartment (Figure 13). Games-Howell post hoc tests revealed no significant difference between the top and bottom logs for either board 0 or 1 (Figure 14). A clear increase from the pith boards to the outer boards is shown. As with the MOE_{edge}, the mean MOR for the outer boards of the bottom log was the highest with the mean MOR for the pith boards of the bottom log the lowest (Figure 14). This highlights the good positive relationship between the two mechanical properties. This is also probably due to the effect of pruning on the outer boards of the bottom log. As with the MOE_{edge}, the pith boards for 1667 stems/ha was similar to the outer boards for the 1334/827 stems/ha compartment showing no significant differences (Figure 15).

The characteristic bending strength of all lumber also improved from pith to bark – 13.4 MPa for the pith boards and 14.7 MPa for the outer boards (Table 6). This increasing trend was reversed for grade S5 lumber with fifth percentiles of 13.6 MPa and 10.1 MPa at the pith and outer boards respectively. Only when all structural grades are considered as S5 the does the characteristic bending strength become greater for the outer boards (14.7 MPa) than for the pith boards (13.9 MPa). A similar result has also been evident in a previous study on South African *P. patula* where all desirable properties of lumber improved with distance from the pith with the exception of the fifth percentile MOR (Wessels et al., 2014). This decreasing trend is also present for 1334/827 stems/ha but less obvious for 1667 stems/ha (Table 6).

Table 6: The MOR per board position and compartments of all lumber for structural grades is shown below. Sample sizes (n) indicated in brackets

SANS Visual grade	All lumber		1334/827 stems/ha		1667 stems/ha	
	Board position		Board position		Board position	
	0	1	0	1	0	1
All	13.4 (121)	14.7 (135)	12.1 (67)	11.5 (71)	20.8 (54)	20 (64)
S5	13.6 (94)	10.1 (44)	12.1 (57)	-	-	-
S5-S10	13.9 (114)	14.7 (133)	12.1 (60)	11.1 (70)	20.8 (54)	20 (63)

The characteristic bending strength of lumber at similar distances from the pith increased considerably from 1334/827 stems/ha to 1667 stems/ha which was consistent with the mean bending strength. Furthermore, the value for the pith boards from the 1667 stems/ha compartment was larger than that of pith or outer boards for 1334/827 stems/ha (Table 6). Possible reasons for the higher MOR values from the denser stand could be both higher wood density (see Figure 16) as well as smaller knot sizes. Densely planted trees normally have smaller branch diameters than widely spaced trees.

3.3 Density

Although density is considered less important than strength and stiffness it remains an essential property for structural timber as it has a positive correlation with strength and stiffness characteristics as well as influencing joint strength in roof trusses. Therefore minimum density values of 360 kg/m^3, 425 kg/m^3 and 475 kg/m^3 are required for SANS structural grades S5, S7 and S10 respectively.

The mean density of boards produced from the 1667 stems/ha compartment was higher than required for S10 grade lumber (Table 2). The mean board density for the 827 stems/ha compartment was sufficient to meet the requirements for grade S7 lumber. As with MOR the density values seem quite sufficient for this resource.

A three-way analysis of variance indicated no significant three-way or two-way interaction between any of the compartment, log position and board position factors (Table 7). Only the main factors of board position and compartment were significant.

Table 7: A three-way analysis of variance for Density. Significant factors at the 5% level are shaded.

Source of variation	SS	Degrees of freedom	MS	F	P
Board position	121348	1	121348	69.40	0.000000
Compartment	181211	1	181211	103.63	0.000000
Log position	1766	1	1766	1.01	0.315892
Board position*Compartment	1197	1	1197	0.68	0.408734
Board position*Log position	5080	1	5080	2.90	0.089559
Compartment*Log position	2382	1	2382	1.36	0.244273
Board position*Compartment*Log position	11	1	11	0.01	0.936821
Error	433651	248	1749		

Log position had no significant effect on board density. Board density could therefore be considered similar in terms of vertical variation – 464 kg/m^3 for the bottom log and 456 kg/m^3 for the top log. The mean density values were greater for the outer boards than the pith boards of both the top and bottom logs (Table 2). The mean board density was 435 kg/m^3 (Std. Dev. = 54 kg/m^3) for the pith boards and 480 kg/m^3 (Std. Dev. = 55 kg/m^3) for the outer boards (not shown in Table 2). The clear increase in density from pith to bark is consistent with previous research (Burdon, et al., 2004, Froneman, 2014; Wessels et al., 2015a). The increase in density from the 1334/827 stems/ha to the 1664 stems/ha compartment can be largely attributed to the decreased ring widths, which would then increase the proportion of latewood. Also, similar board positions from the slower growing 1667 stems/ha compartment will have older year rings with higher cambial age and therefore also higher density. The mean board density was 435 kg/m^3 (Std. Dev. = 42 kg/m^3) for the 827 stems/ha compartment and 490 kg/m^3 (Std. Dev. = 55 kg/m^3) for the 1667 stems/ha compartment (Table 2).

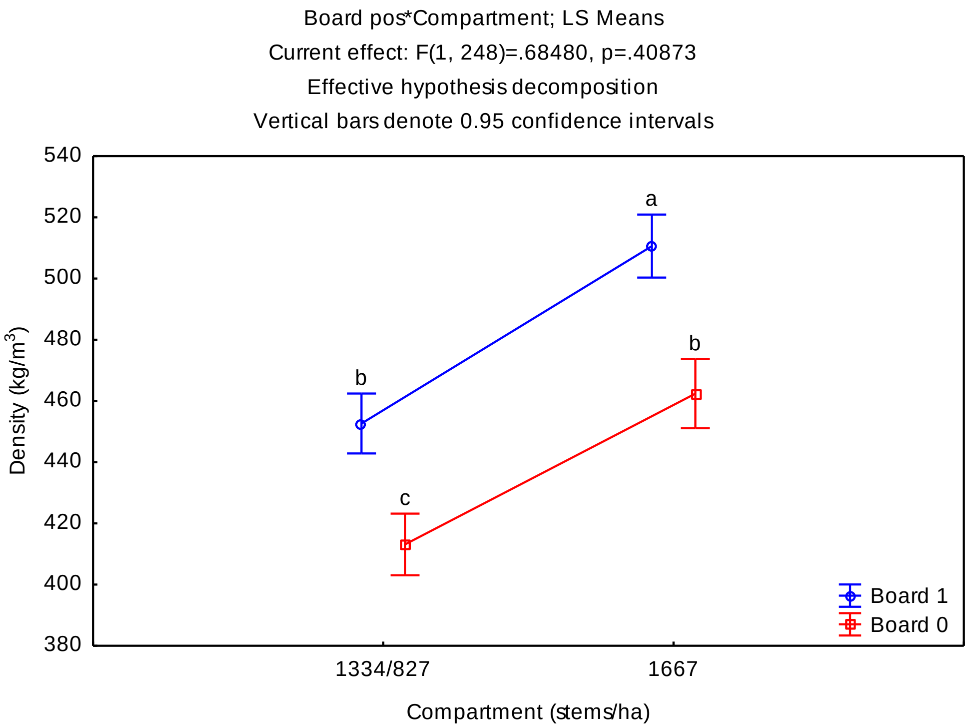

Figure 16: Means and 95% confidence intervals for density of different board positions for 1334/827 stems/ha and 1667 stems/ha. Different letters denote significant differences

The density of lumber at similar distances from the pith increased significantly from 1334/827 stems/ha to 1667 stems/ha (Figure 16). This result was consistent with both the mean MOE_{edge} and mean bending strength and was probably partly the reason for these higher strength and stiffness values. Density values for the pith boards from the 1667 stems/ha compartment, on average, showed no significant difference compared to that of outer boards for 1334/827 stems/ha (Figure 16).

3.4 Ring width

The mean, minimum and maximum ring widths for board positions, log position and compartments are shown in Table 2. Figures 17 and 18 shows the cross-sectional images with the mean ring widths per planting density treatment with a typical cant sawing pattern (40 x 120 mm) superimposed on it. Ring width is an important property since it affects the geometry of sawing and subsequently the individual board properties. The mean ring width reduced from 8.4 mm for 1334/827 stems/ha to 7.7 mm for 1667 stems/ha. A greater reduction is shown for the maximum ring widths – 15.3 mm to 12.5 mm (Table 2). The maximum ring width is typically located close to the pith and generally decreased from pith boards to outer boards (Table 2).

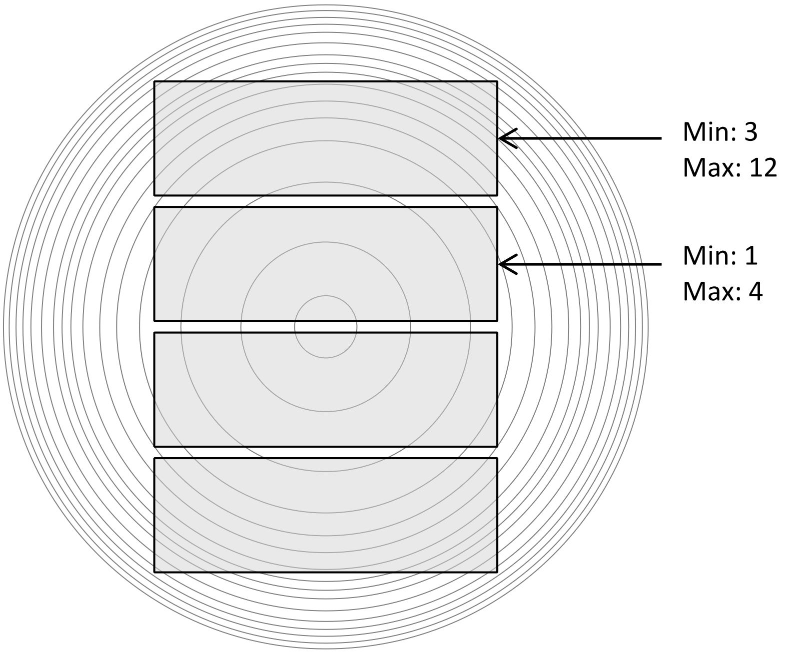

Figure 17: The mean ring widths for 1334/827 stems/ha overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position

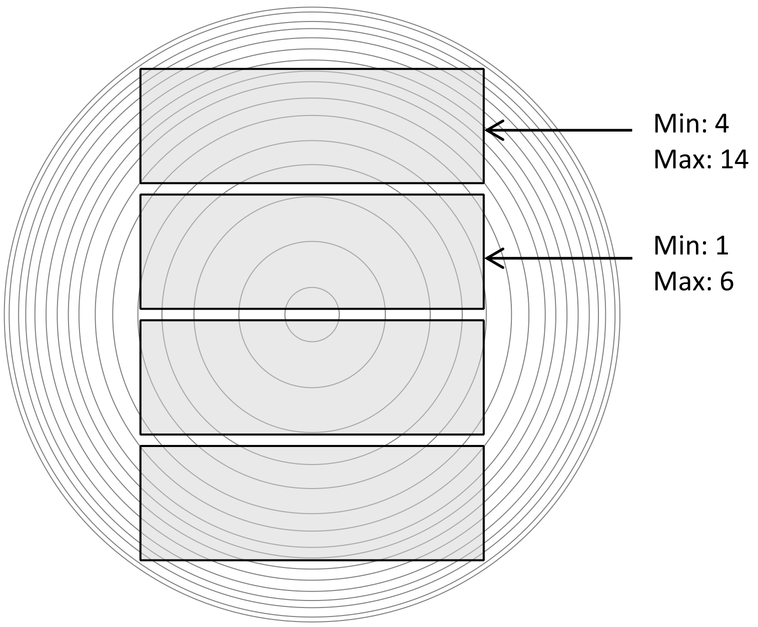

Figure 18: The mean ring widths for 1667 stems/ha overlaid with a 40 x 120 mm cant sawing strategy drawn to scale including a saw kerf of 4 mm. Maximum and minimum rings are indicated for each board position

Rings further away from the pith are known to have improved wood properties (Burdon et al., 2004). Smaller ring widths ensure that older, more mature annual rings with better properties are closer to the pith. Figure 17 shows ring four to be the maximum annual ring present in the pith boards for 1334/827 stems/ha. This is based solely on board ends. The large rings close to the pith are reduced for 1667 stems/ha, increasing the maximum ring present in pith boards and outer boards by two (Figure 18). Although this increase seems small, it should reduce the mean microfibril angle and increase the mean density which improves the stiffness.

3.5 Warp (bow, spring and twist)

The permissible values for bow according to SANS 1783-2 (2012) are per 1 m of a lumber piece, whereas for spring and twist the values are over the full test length of specimens. Bow and spring values were only recorded over 2 m and were expressed as mm/m. Twist was recorded at the maximum angle over the 2 m. The values for spring in mm/m were therefore multiplied by the nominal length (2.4 m) for the full length of lumber pieces.

Analysis of variance showed that compartment (p=0.1189), board position (p=0.4452) and log position (p=0.3365) did not have a significant effect on twist. The mean values for different board positions, log positions and compartments were therefore very similar (Table 2). The mean twist for all the boards as seen in Table 2 was 1.9° (standard deviation = 1.7°) and appears sufficient for this resource in relation to the 4-5° limit. There were too few values for spring due to testing errors to run ANOVAs. The mean spring values did not vary much between factor levels. The average values for all spring measurements was 1.7 mm (St. Dev. = 0.8 mm) which was well below the 15 mm limit (Table 2).

Table 8: A three-way analysis of variance for Bow. Significant factors at the 5% level are shaded.

Source of variation	SS	Degrees of freedom	MS	F	P
Board Position	7.9807	1	7.9807	5.0555	0.025430
Compartment	0.0506	1	0.0506	0.0321	0.858015
Log position	12.0396	1	12.0396	7.6266	0.006183
Board position*Compartment	1.6292	1	1.6292	1.0320	0.310682
Board position*Log position	1.2611	1	1.2611	0.7989	0.372296
Compartment*Log position	0.0468	1	0.0468	0.0296	0.863495
Board position*Compartment*Log position	0.0030	1	0.0030	0.0019	0.965200
Error	389.9202	247	1.5786		

A three-way analysis of variance was done for bow with board position, log position and compartment as the main effects (Table 8). Results showed only board position and Log position to have a significant effect on bow. The mean bow for all pith and outer boards was quite low at 1.8 mm/m (St. Dev. = 1.3 mm/m) and 1.5 mm/m (St. Dev. = 1.3 mm/m) respectively. Mean values were much lower than the 10 mm/m limit were also found for the top and bottom log at 1.4 mm/m (St. Dev. = 1.3 mm/m) and 1.9 mm/m (St. Dev. = 1.3 mm/m) respectively.

The low twist results in this study were quite interesting as it differed quite significantly from previous research showing huge problems with twist of young South African-grown *P. patula* (Dowse and Wessels, 2013; Wessels et al., 2014). Both the studies referred to reported the twist of lumber to be well above the allowed twist with more than half of the lumber being rejected – based soley on twist. Additionally, Wessels et al. (2014) found the radial position of lumber to be influential and accounted for 18.5 % of the variation in twist. This too, was different to the insignificant effect of board position (p=0.4452) on twist in this study.

Overall, the average values for all forms of warp for this resource were sufficient as they all were well under the limit for structural lumber (Table 2).

3.6 Relationship between different properties

All correlation coefficients (r) between the measured properties are shown in Table 3.

MOE_{edge} vs. MOR

One of the most widely used relationships is that between MOE and MOR obtained through bending tests. It has been reported that this relationship is weaker in young material than in mature wood (Gaunt, 1999). The relationship between these two properties in this study (R^2=0.7) was relatively strong in comparison to recent studies on SA pine resources (Wessels et al., 2011; Dowse and Wessels, 2013; Froneman, 2014). Dowse and Wessels (2013) obtained a coefficient of determination of R^2=0.48 for young *P. patula*, while Froneman (2014) found a slightly higher R^2 of 0.54 for 20 year-old *P. radiata*. It was also marginally better than the expected range reported by Gloss (2004) and comparable to a study on Norway spruce (Johansson et al., 1992). The relationship in this study was still quite high even when separating the boards according to compartment, with no obvious difference between the two (Figure 19 and Table 9).

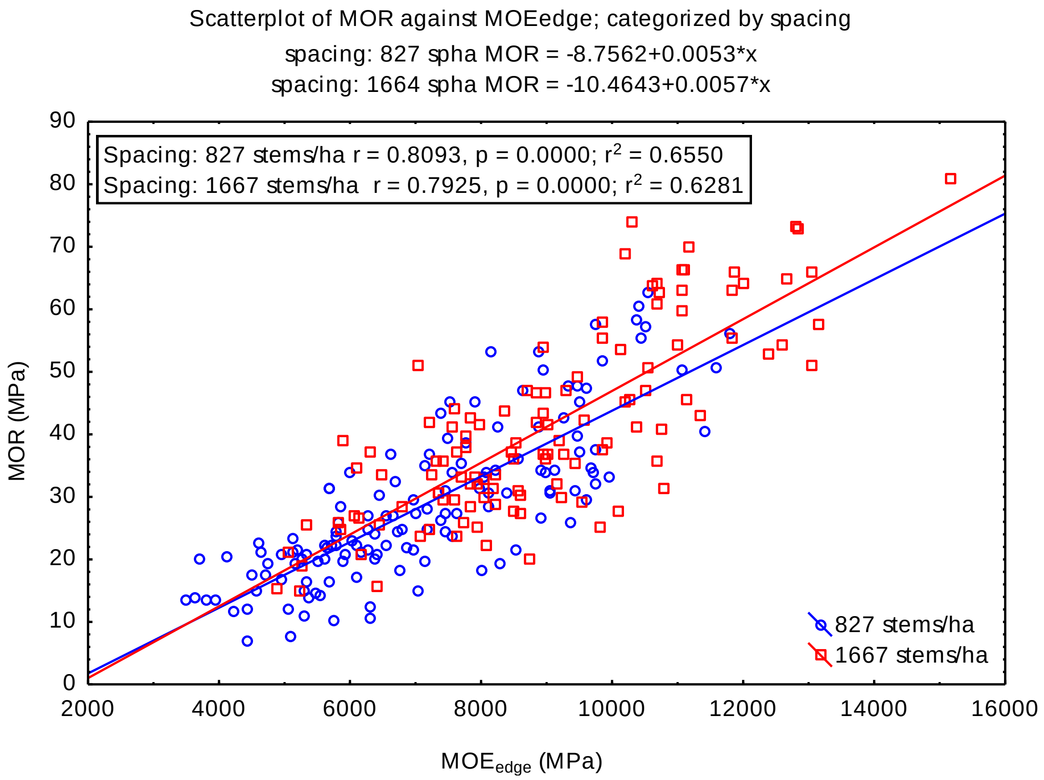

Figure 19: Scatterplot and regression line of MOR against MOEedge for all groups (R^2=0.7). For the 1334/827 stems/ha plot (R^2=0.66) and the 1664 stems/ha plot (R^2=0.63).

Table 9: Visual grade yield and the MOE_{edge}–MOR relationship (R^2) for board and log position and compartment

Description		All boards	Board position		Log position		Compartment (stems/ha)	
			0	1	bottom	top	1334/827	1664
Number of boards		260	121	135	133	123	141	119
Visual grade yield (%)	xxx	3.5	5.8	1.5	2.2	4.9	5.7	0.8
	S5	53.1	77.7	32.6	48.2	58.5	60.3	44.5
	S7	18.5	13.2	23.7	16.1	21.1	17.0	20.2
	S10	25.0	3.3	42.2	33.6	15.4	17.0	34.5
MOE vs MOR (R^2)		0.70	0.60	0.67	0.77	0.56	0.66	0.63

Although separating the boards according to their compartments showed no clear change in this relationship (Figure 19 and Table 9), the proportion of S7 and S10 lumber were greater for the 1664 stems/ha compartment. The MOE_{edge}–MOR relationship improved from the top (R^2=0.56) to the bottom log (R^2=0.77) (Figure 20 and Table 9). Furthermore this relationship remains constant at the top log for each board position 0 and 1 separately at R^2= 0.56 (not shown in Table 9) while the bottom log displays an improved relationship from board 0 to 1 (R^2 = 0.64 to 0.73). This increase could be explained by the improved overall grade recovery of higher strength grades for the bottom log (Table 9). The down-grading of lumber was in most cases due to large knots, which highlighted the effect of pruning on the outer section of the bottom log. The smaller difference in the MOE_{edge}–MOR relationship between the pith boards of the top and bottom log is therefore supported by the fact that there were no clear difference in the XXX and grade S5-10 yield distributions for the pith boards of top and bottom logs (Table 10).

Table 10: Structural grade distribution for pith boards

SANS visual grade	Grade yield (%)	
	Top log	Bottom log
XXX	8.6	3.2
S5	77.6	77.8
S7	13.8	12.7
S10	0.0	6.3

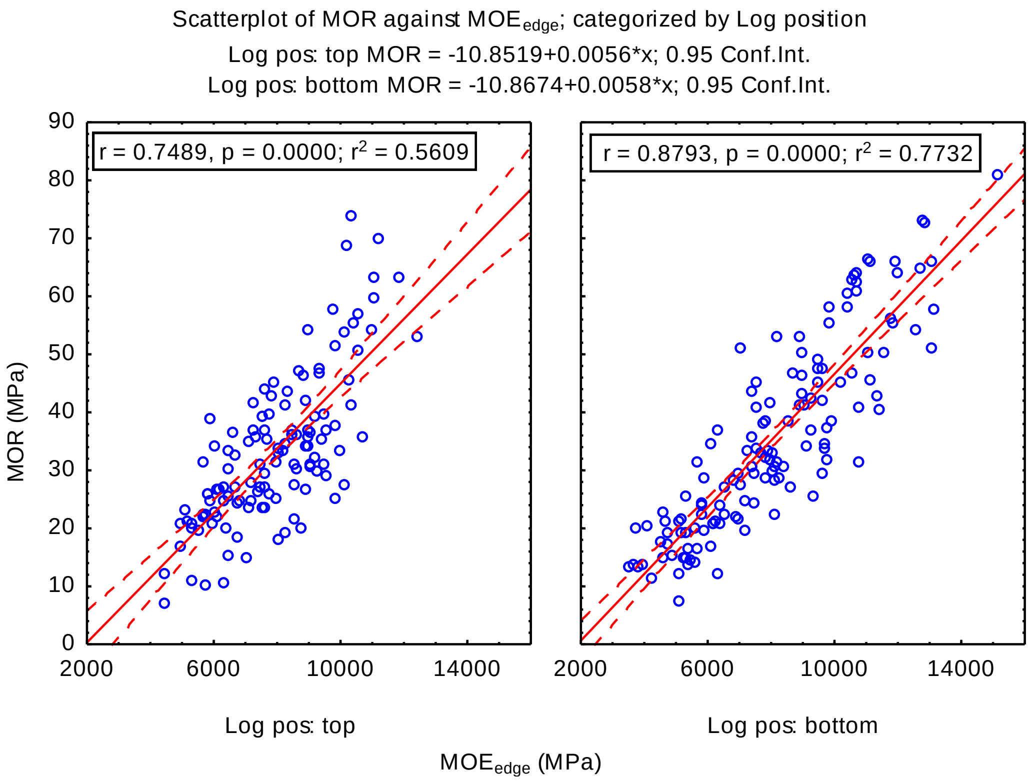

Figure 20: Scatterplot of MOEedge against MOR for the top and bottom logs each

MOE_{dyn} vs. MOE_{edge}

In this and other studies (Dowse and Wessels, 2013; Froneman 2014), the dynamic MOE was the best single non-destructive predictor of stiffness (MOE_{edge}) and strength (MOR). MOE_{edge} – determined destructively – was only slightly better than MOE_{dyn} at predicting MOR (Table 3). This non-destructive evaluation of MOE as a simple, cost effective method of strength grading would be very useful in this case as a relatively strong relationship between strength and stiffness is displayed for this young lumber resource. The relationship between MOE_{dyn} and MOE_{edge} is displayed in Figure 21. The MOE_{edge} was slightly overestimated by MOE_{dyn} at higher values. The MOE_{dyn}–MOR (R^2=0.64) relationship also did well compared to the MOE_{edge}–MOR relationship.

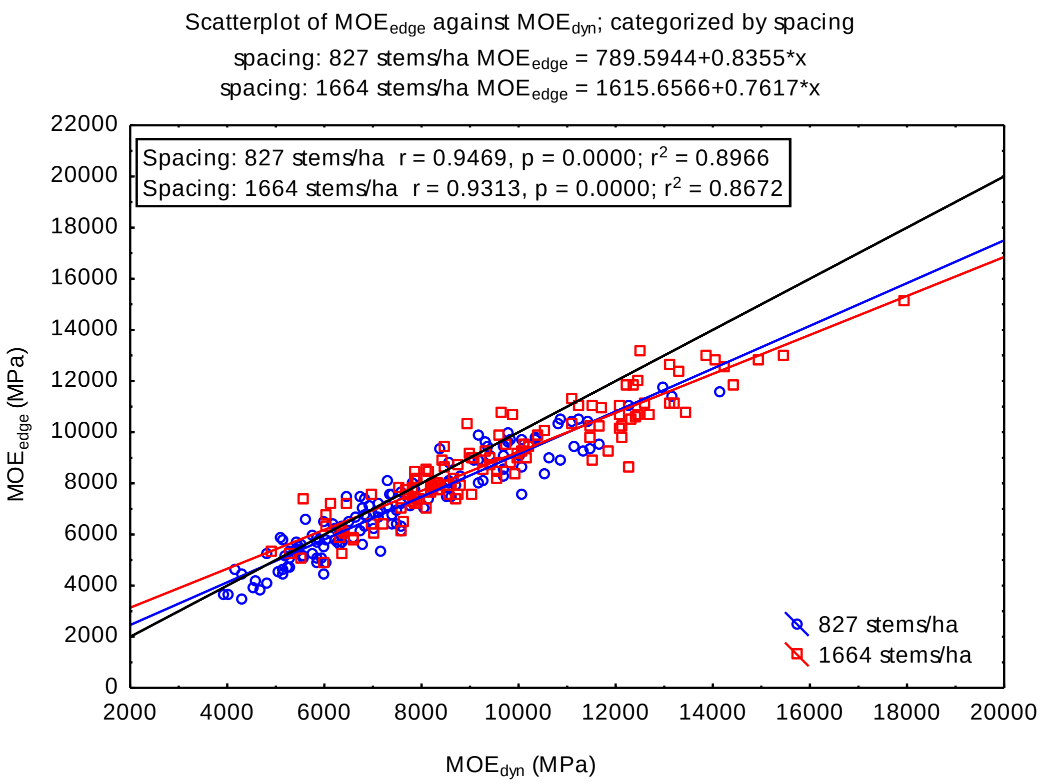

Figure 21: Scatterplot and regression (solid) line of MOE_{dyn} against MOE_{edge} for all groups (R^2 = 0.9). Black line indicates 1:1 relationship

Other properties

Other properties, which significantly influenced lumber strength and stiffness, include ring width, cambial age and real age (Table 3). Among these three properties, the strongest relationships with both MOR and MOE_{edge} each were with the mean cambial age and the maximum ring width. The significant positive influence of the mean cambial age highlights that as boards move away from the pith the stiffness improved. While the significant negative relationship with the maximum ring width illustrates how the restriction of corewood through smaller annual rings improved the overall stiffness. Twist and spring showed no significant correlation with any variable (Table 3) while all forms of warp (including bow) generally displayed poor and insignificant relationships with other variables. It must be mentioned that these results might differ for other processing plants using different drying methods and schedules.

3.5 Multiple regression analysis

A multiple regression model was developed for MOE_{edge} using tree and board properties. The DBH, density and the maximum ring width of lumber were all significant parameters in the model (Table 11). This model explained 66% of the variation in MOE_{edge}. The observed vs predicted values are shown in Figure 22. A slight over prediction of MOE_{edge} is displayed for higher values, while low MOE_{edge} are under-predicted. Sensitivity analysis on the regression model indicates the influence of each variable on the modelled MOE_{edge}. The mean, 5^{th} percentile and 95^{th} percentile of DBH, density and the maximum ring width were calculated from the observed values of each variable. In the model, the change in MOE_{edge} was recorded as the input of a particular variable was changed from its 5^{th} percentile to its 95^{th} percentile, while all other variables were held constant at their mean observed values. One by one, this step was completed for each variable.

Table 11: A multiple regression model for MOE_{edge} of all 260 lumber pieces (R^2 = 0.66) (F-statistic: 163.2 on 3 and 256 DF, p<0.0001) (shaded parameters were significant at p<0.05)

Regression model		Sensitivity analysis				
	Parameters	Mean	5^{th} perc	95^{th} perc	Δ MOE_{edge} (MPa)	Influence (%)
Intercept	2222.2					
DBH	-96.7	28.5	23.8	37.3	-1305.2	18
Density	23.1	460.0	385.1	558.9	4016.3	54
Max ring width	-152.2	14.0	8.0	21.4	-2049.8	28

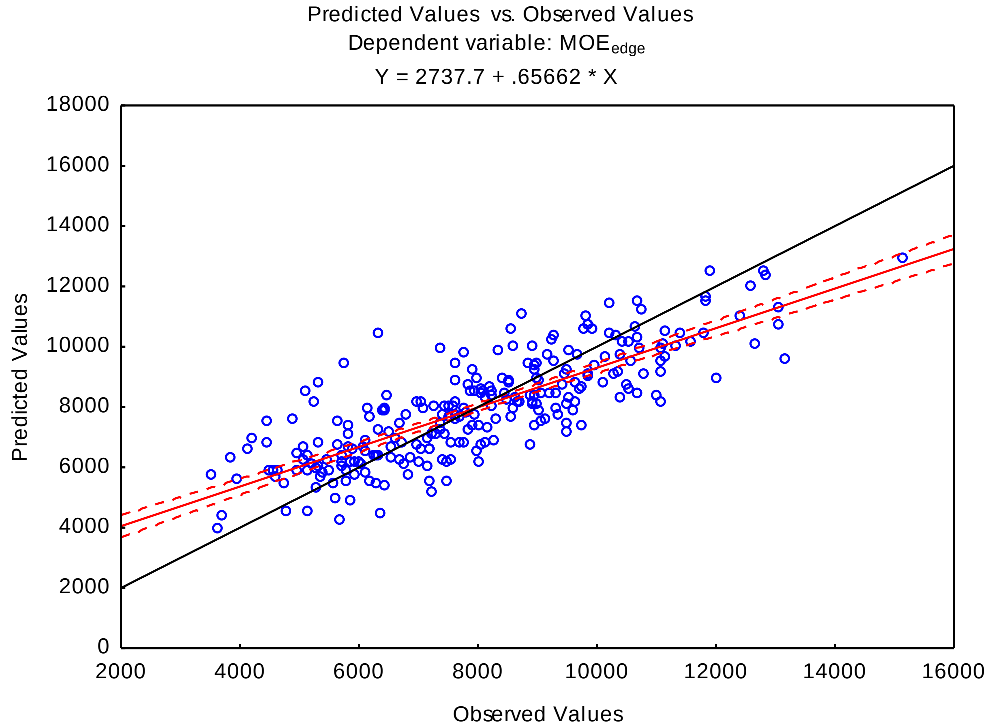

Figure 22: Predicted vs observed values of a multiple regression model for $MOE_{edge.}$ The model and 95% confidence intervals and the 1:1 line are shown

The density of lumber was the most influential of all explanatory variables in accounting for MOE_{edge} variation with an "influence" value of 54%. The maximum ring width entered the multiple regression model as a negative parameter. It was about half as influential as density (28%). The maximum ring width was typically located close to the pith and gradually decreased thereafter. The earliest annual ring present in board ends should represent the maximum ring width. The model thus indicated that a reduction in the largest annual rings improved the MOE_{edge} of lumber. A similar finding is reported by Wessels et al. (2014). Reduced maximum ring widths should also increase the slenderness of trees, which is suggested to improve the trees resistance to buckling of the stems and consequently improve its MOE (Watt et al., 2006; Merlo et al., 2014; Wessels et al., 2015b). Slenderness of trees did not however contribute significantly to the model and was excluded. This result is quite different from the strong positive relationship between slenderness and wood stiffness reported by other studies (Lasserre et al., 2005; Watt et al., 2006; Roth et al., 2007; Watt et al., 2009). DBH entered the model as a significant negative parameter and accounted for

18% of the MOE_{edge} variation. This model will only be valid for trees in the age range sampled for this study and might well be different for other age ranges.

3.6 Radial, longitudinal and between-compartment variation in properties

All the important properties improved with distance from pith with the exception of the fifth percentile MOR – which is more relevant than the mean MOR – for grade S5 lumber. This result has also been reported in a previous study on young *P. patula* (Wessels et al., 2014). The main reason behind the influence of board position on wood properties may be attributed to the high pith to bark variability of corewood properties such as MFA and density.

The influence of log position was relatively small compared to board position and unlike results by Wessel et al. (2014) had no significantly effect on any variable. Although still insignificant the differences were greatest at the outer boards which were probably due to the effect of pruning where outer boards of the bottom logs should contain a large portion of knot-free lumber due to pruning. This corresponds with the percentage of S10 timber of the bottom log (33.6%), which was roughly double that of the top log (Table 9). The top log had higher proportions of lower structural grades S5 and S7 as well as the non-compliance grade XXX.

Compartment or spacing treatment had a significant effect on MOE, MOR and density. The mean values for these properties were highest at the denser planted compartment (1667 stems/ha). Only warp (bow and twist) was not statistically different between compartments.

3. Conclusions

Based on the results from this study, the following conclusions were made:

- Lumber from the 1667 stems/ha compartment had a mean MOE_{edge} of 8967 MPa compared to a mean MOE_{edge} of 7134 MPa for the 1334/827 stems/ha compartment. In a previous study on 16-20 year-old *Pinus patula* from the same region which was planted at standard saw-log regime densities and thinned up to three times, a mean MOE_{edge} of 5755 MPa was obtained (Wessels et al., 2014). Based on this evidence it seems as if planting density has a large effect on the stiffness of young *Pinus patula* lumber. It should be noted, however, that site and genetics could have been responsible for some of the differences.
- The characteristic MOR for both compartments complied with requirements for structural grade lumber. This confirms the relatively good bending strength of young

Pinus patula lumber. The characteristic MOR for the 1667 stems/ha compartment (20.8 MPa) was much higher than that of the 1334/827 stems/ha compartment (12.1 MPa).

- The minimum required density of structurally graded lumber is 360 kg/m^3. The mean board density of the 1334/827 stems/ha compartment was 435 kg/m^3 and for the 1667 stems/ha compartment 490 kg/m^3 – which were both well above the minimum requirements. Density was significantly affected by both board position and compartment. Higher density wood of the 1667 stems/ha compartment was undoubtedly part of the reason for the better stiffness lumber.

- Contrary to previous research on young South African *P. patula* the twist of this resource was relatively low and far below the allowed limit for structural grade lumber. Planting density showed no significant effect on bow or twist.

- The Pearson correlation between MOR and MOE_{edge} for this resource was relatively high (R^2=0.7) ensuring effective grading based on this relationship. The reason for the better than expected correlation is not very clear. This correlation was slightly higher for the bottom log lumber and considerably lower for top log lumber.

Based on the evidence from this study it seems as if planting density has the potential to improve the stiffness of *Pinus patula* lumber considerably. However, the study used commercial compartments from different sites (but close to each other) which obviously did not receive identical management interventions. It will be much better if the study can be repeated on a spacing trial where the effect of planting density can be determined over a wider range of spacings, on trees which grew in identical circumstances.

Thinning of compartments is standard practice for saw log management regimes in South Africa in order to maximise diameter growth in trees and remove poor stem form trees. Future work should focus on quantifying the effect of thinning on densely planted compartments. Of interest will be the timing of thinning to still obtain the benefit of increased stiffness of the corewood through early suppression of growth but maximising diameter growth over the life of the compartment. Diameter plays an important role in volume recovery in sawmills.

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Chapter 4

Conclusions and recommendations

The first investigation where an 18-year old *Pinus patula* spacing trial was non-destructively sampled confirmed the significant effect that planting density has on MFA – one of the main drivers of lumber stiffness. It was shown that the combined effect of slower growth and lower MFA values has a profound effect on the mean board MFA and to a lesser extent also on board density. Apart from lower absolute values, MFA seems to stabilise much earlier (7^{th} to 8^{th} growth ring) in densely planted trees, compared to less densely planted trees (10^{th} to 11^{th} year ring).

The second investigation on two commercial compartments showed large differences in lumber stiffness between the 1667 stem/ha and the 1334/827 stems/ha compartments. The mean MOE_{edge} values in this investigation were also much higher than found in a previous study where similar aged trees grown on conventional saw-log regime were tested.

Both studies thus confirm the potential that higher planting density has for improving lumber stiffness of young *Pinus patula* trees.

These investigations were from the same region and results should ideally be confirmed by testing trees from different growth sites and regions.

The following recommendations were made:

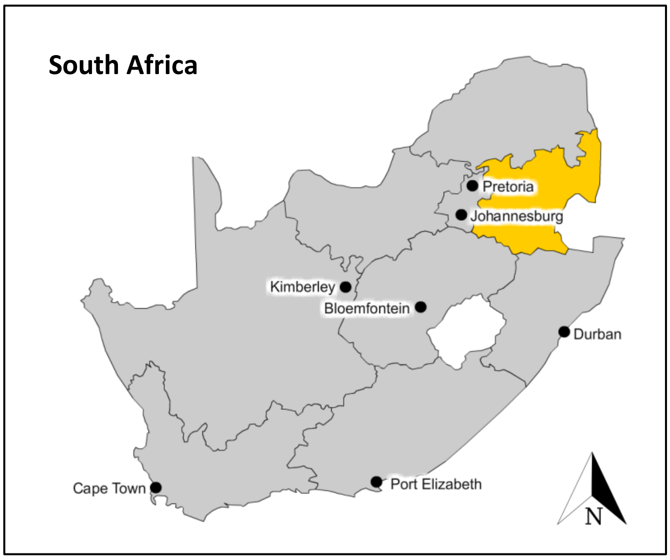
– If spacing trials become available for destructive sampling, lumber should be tested for stiffness over a wide range of planting densities to confirm these results, and better quantify the effect of planting density on end-product stiffness.

– More work is required to understand the effect of planting density on stem form including the possible effect of thinning.

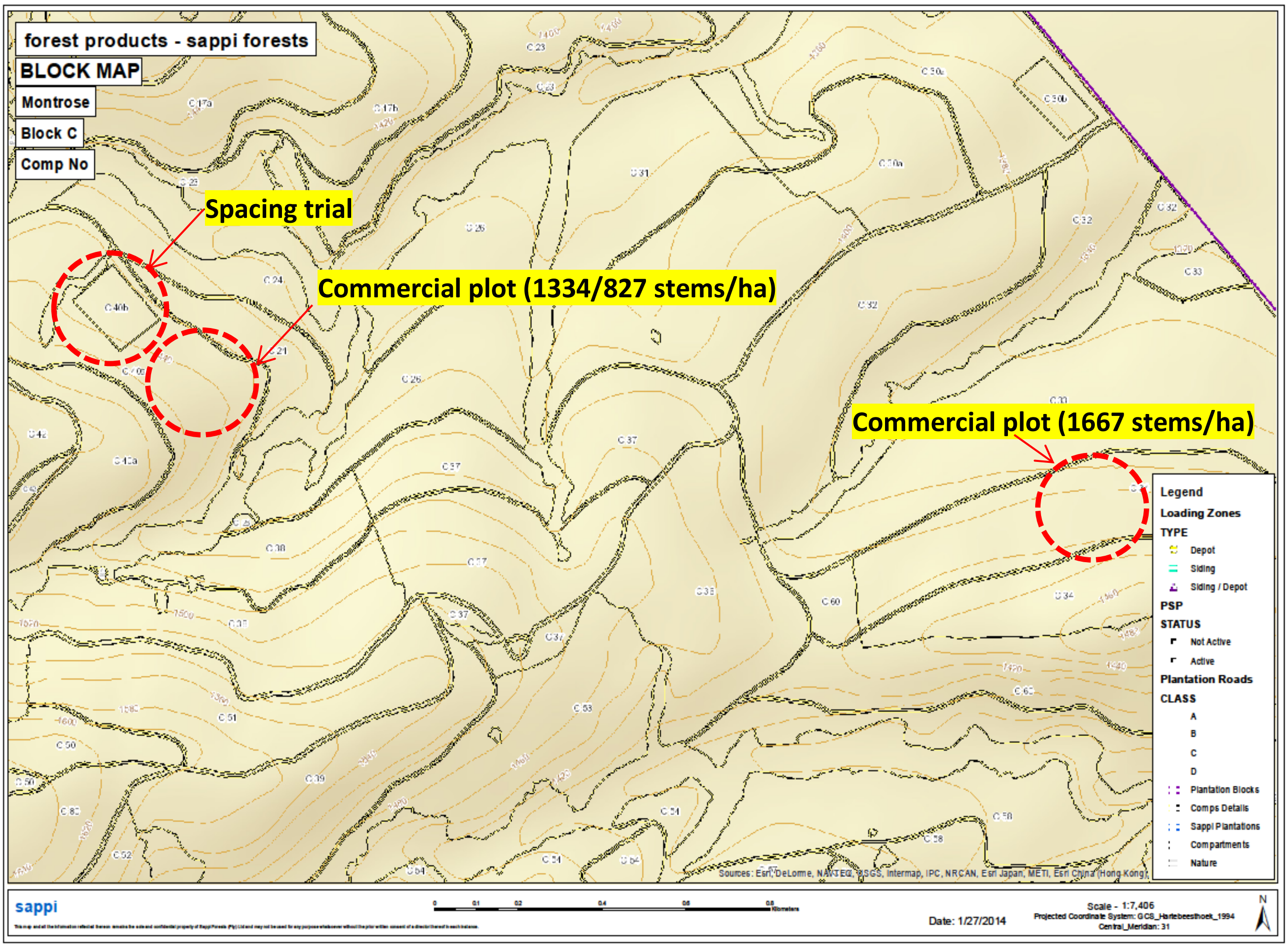
– The effect of thinning on MOE, including the timing thereof, should also be quantified on the lumber processed from densely planted compartments.

– The effect of various site qualities should be determined to evaluate their additional impact on wood stiffness.

Addendum A: Location of Barberton, commercial compartments and the spacing trial



Addendum B: Location of commercial compartments and spacing trial at the Montrose management unit



Addendum C: Location of spacing trial treatments